

Using Bond Graphs for Articulated, Flexible Multi-bodies, Sensors, Actuators, and Controllers with Application to the International Space Station

Raymond C. Montgomery, AST
Dynamics and Control Branch
NASA Langley Research Center
Hampton, Virginia 23681 USA
r.c.montgomery@larc.nasa.gov

Jose J. Granda, Professor
Department of Mechanical Engineering
California State University Sacramento
Sacramento, Ca 95819 USA
grandajj@ecs.csus.edu

Keywords: Space Station, bond graphs, CAMP-G, flexible body dynamics, computer models, state space

ABSTRACT

Conceptually, modeling of flexible, multi-body systems involves a formulation as a set of time-dependent partial differential equations. However, for practical, engineering purposes, this modeling is usually done using the method of Finite Elements, which approximates the set of partial differential equations, thus generalizing the approach to all continuous media. This research investigates the links between the Bond Graph method and the classical methods used to develop system models and advocates the Bond Graph Methodology and current bond graph tools as alternate approaches that will lead to a quick and precise understanding of a flexible multi-body system under automatic control. For long endurance, complex spacecraft, because of articulation and mission evolution the model of the physical system may change frequently. So a method of automatic generation and regeneration of system models that does not lead to implicit equations, as does the Lagrange equation approach, is desirable. The bond graph method has been shown to be amenable to automatic generation of equations with appropriate consideration of causality. Indeed human-interactive software now exists that automatically generates both symbolic and numeric system models and evaluates causality as the user develops the model, e.g. the CAMP-G software package. In this paper the CAMP-G package is used to generate a bond graph model of the International Space Station (ISS) at an early stage in its assembly, Zvezda. The ISS is an ideal example because it is a collection of bodies that are articulated, many of which are highly flexible. Also many reaction jets are used to control translation and attitude, and many electric motors are used to articulate appendages, which consist of photovoltaic arrays and composite assemblies. The Zvezda bond graph model is compared to an existing model, which was generated by the NASA Johnson Space Center during the Verification and Analysis Cycle of Zvezda.

INTRODUCTION

Many of the International Space Station components and sub-assemblies have been modeled originally using the Finite Element Method. Software such as NASTRAN, SOMBAT for non-linear finite element models, and DSAT for linear models and the control systems have been used to perform dynamic analysis and control simulations of ISS. In modeling, NASTRAN is used to create modal models of subassemblies wherein great detail is undertaken in the finite element analysis. SOMBAT is used to put the modal models together taking into account possible articulation of some of the subassemblies as needed. The theory underlying SOMBAT is Treetops, reference (1), which is based on Kane's method, reference (2). These simulations tend to be computationally intensive depending on the number of modes used in representing the assemblies. In order to study the influence of the controls on the structure in a less computationally intensive manner and

still include a large number of modes, the non-linear finite element models are linearized at operating points and frequency response analysis applied. Such linearization about particular operating points produces a state space model, which is suitable for analysis with software tools such as MATLAB and SIMULINK, and which can be input directly in the a MATLAB-based analysis tool developed by the Draper Laboratory, DSAT, Jang, Jiann-Woei, N. Bedrossian, and E. McCants [3]. Since the bond graph method generates state space representations also, a link can be established as a common ground for the representation of physical systems.

The Treetops approach to the verification of control systems for articulated, flexible, multiple bodies is to generate, via finite element analysis, modal models that satisfy attachment boundary conditions for each articulated body. A composite model that includes all bodies is then constructed by connecting the individual modal models via joints, which allow the desired articulation but otherwise satisfy the motion constraints of the attachments. A parametric control system is then postulated and closed-loop performance is analyzed either by simulation, or by analysis, or both.

The approach outlined above has been taken to verify the control/structure interactions during assembly of the International Space Station (ISS). The ISS assembly process is evolutionary, that is, several missions must be completed before the ISS reaches the Assembly Complete configuration as shown in Figure 1. Jorgensen [4] describes the assembly sequence. The space station is a space laboratory, which circles the earth about every 90 minutes. Each assembly mission leaves the ISS as a more complex, and more flexible structure, and in many cases one having more articulated parts. It is our objective here to reduce the complexity of modeling the individual missions and illuminate the number of modes necessary to understand the dynamic behavior yet retain the necessary information to predict reliably the dynamic response of the system to the different inputs, which are forces and moments which reboost the ISS for orbit maintenance, perform maneuvers, and articulate appendages to track the sun with the photovoltaic arrays (PVA's) and the shade with heat rejection assemblies. Figure 2 illustrates the operation of the appendage rotation assemblies for the ISS as it circles the earth and tracks the sun.

Focusing on rigid body dynamics and the bond graph method, Karnopp, Margolis, Rosenberg [5] describe the representation of a bond graph of three dimensional rigid body motion in a three dimensional space. Principles underlying the bond graph representation of flexible bodies have been put forth by Karnopp, Margolis [6] and the computer generation of differential equations using bond graphs was established as a viable way to simulate dynamic systems by Granda [7]. Further developments have led to the principles behind computer generation of models in the state space form in Granda, Reus [8] and fundamentals of computer generated transfer function for multi-output, multi-input systems was established by Granda [9].

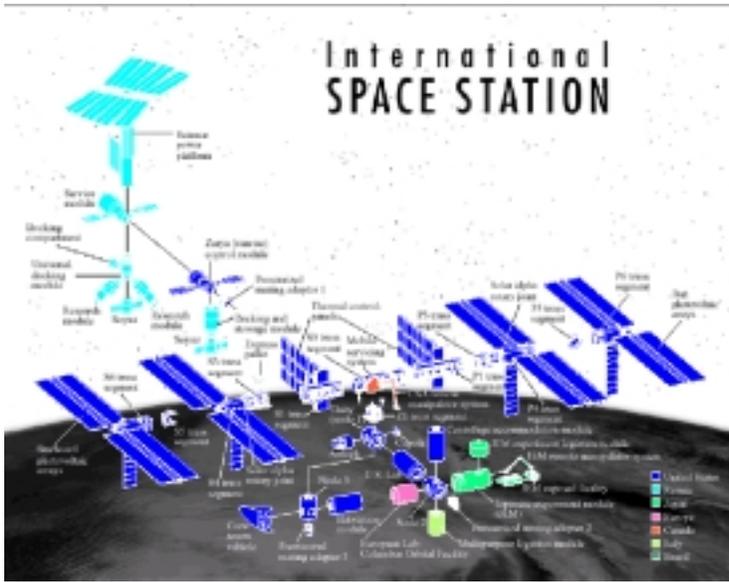


Fig 1. ISS Assembly Complete Configuration

Using this background consider that the mathematical State Space representation has been used to write the equations of motion to represent a linearized version of the Space Station. Such state space models have been generated at several operating points of the configuration. This means linearization about several attitudes and positions. This paper presents a bond graph modeling methodology for a set of flexible multi-bodies with the objective of producing also the state space form. CAMP-G is a tool to achieve this in symbolic form and in numeric form. The control system used for this research is the Russian Segment Controller, developed to provide attitude control and reboost capability for the different configurations of the space station. Such physical plant is subject to the feedback provided by sensors and the inputs provided by the actuators to control the station. Such actuators physically are jets attached to the different modules of the station, which control the forces and torques in all six degrees of freedom, whether to position the station or to rotate it around the roll, pitch and yaw axes.

MATHEMATICAL FOUNDATION

The finite element method is used to model and analyze distributed systems in the context of continuous media. The method is widely used in analysis of structures, frames, heat transfer and dynamic analysis. The latter involves the solution of partial differential equations with time dependencies. The differential equations governing time-dependent field problems has the form:

$$D_x \frac{\partial^2 \phi}{\partial x^2} + D_y \frac{\partial^2 \phi}{\partial y^2} + D_z \frac{\partial^2 \phi}{\partial z^2} - G\phi + Q = \lambda \frac{\partial \phi}{\partial t} \quad (1)$$

Here ϕ is the field function (solution) and the parameters in the equation are D_x , D_y , D_z the stiffness in the x, y, and z directions, and λ is the coefficient for the time dependant term. These parameters are generally constructed from material and geometric properties and the solution is sought over a domain in x, y, and z. Practical solutions of the above include the popular finite-element method, a detailed solution of which is presented

Sun Tracking with the α and β Joints Shading with γ Joints

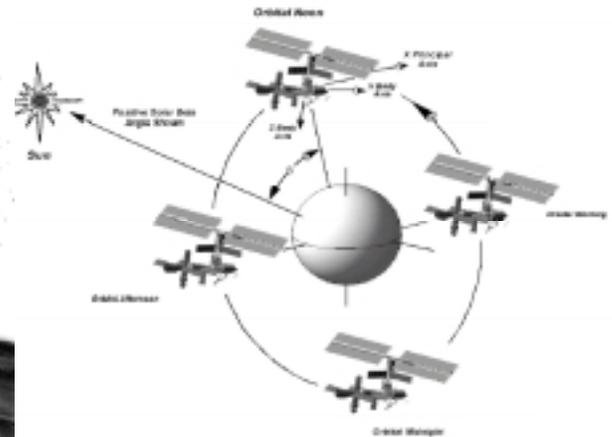


Fig 2. Space station around earth, sun tracking

by Segerlind [11]. Therefore, only a short summary is included here. For the finite element method the region under consideration is divided into sub domains appropriately called, finite elements. The partial differential equation is solved for each class of element over its associated sub domain. There are several methods available to implement a practical solution. Two of the most popular are the Galerkin method and the Calculus of Variations. In any case, the objective is the same, to find an approximate solution for the partial differential equations and to do it in such a way as to reduce the finite element problem to a set of linear algebraic equations whose unknowns are called nodal values, in this case these nodal values are the positions and velocities of points of interest on the different bodies which make up the ISS.

Galerkin methods, for example, fall under a general class of methods known as the weighted residuals [8]. In these methods, an approximate parametric solution to the partial differential equation is constructed from a linear combination of shape functions. This parametric form is substituted into the governing differential equation, Equation (1), and a measure of the resulting error, or residual, which is integrated and required to vanish over the domain of the solution, produces the set of algebraic equations whose unknowns (nodal values) are positions and velocities at points of interest in the ISS structure.

In Segerlind [11], it is shown that applying the weighted residual methods, such as Galerkin's method, one can obtain the system of equations in terms of the time dependent nodal values. Denoting as $f(t)$ the time dependent forcing function and Φ as the nodal values, one obtains equations of the form:

$$[c^{(e)}] \{\dot{\Phi}\}^{(e)} + [k^{(e)}] \{\Phi\} - f^{(e)} = \{0\} \quad (2)$$

Where $[c, k$ and $f]$ are the individual finite element mass, stiffness and load vectors. By means of the direct stiffness method, as explained in Reference [11] the element vectors and matrices can be summed over all the finite elements resulting in global vectors and matrices. Equation (3) represents

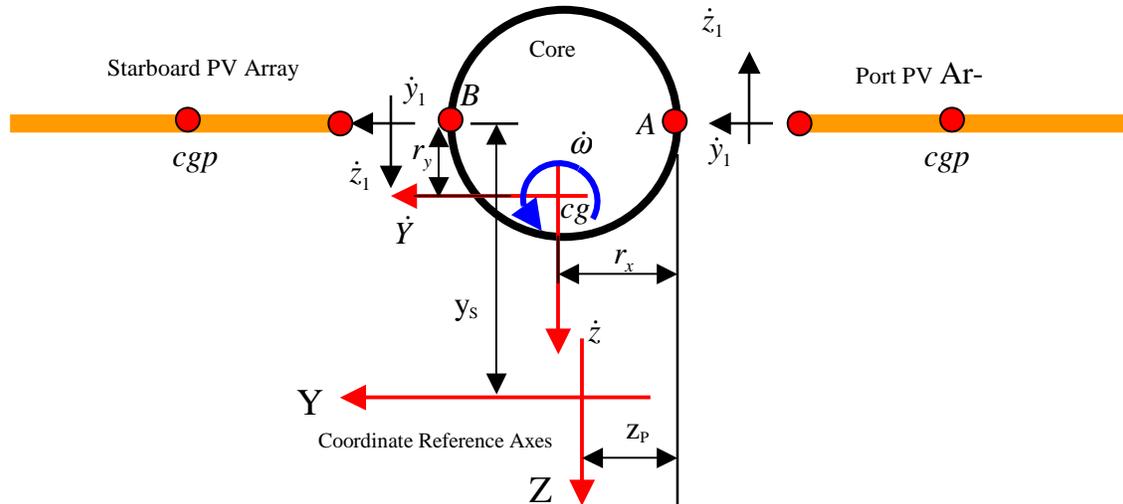


Fig 5. Two dimensional Models

Now it is necessary to consider the kinematics of the center of mass of the PVA'S and the flexible modes of this cantilever array. Thus we obtain the bond graph shown in Fig 6 where the angular velocity and linear velocities of the center of mass of the PVA are represented by the 1 junction at the right. Notice that derivative causality is present on the inertia elements of the PVA center of mass. This is due to the fact the translation mass in the Y and the Z directions should be combined instead of considering three independent I elements.

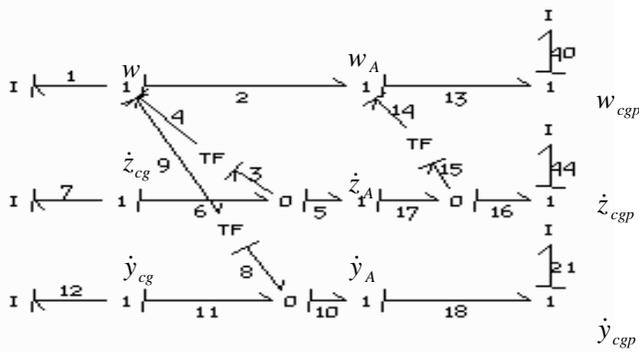


Figure 6. Kinematics of the core and PVA's bodies at their center of mass.

Now what is left is to add the flexibility to the PVA. The Karnopp, Margolis [6] approach was used to represent the flexibility starting with rigid body modes and adding the flexibility considering the modes as close to a beam model. C elements have been added in order to avoid any derivative causality conflicts and produce a computational model according to the approach of Margolis, Karnopp [5]. It is obvious that this model can still be further simplified and Inertia effects at the center of mass of the PVA's be combined with those of the core, again, to avoid derivative forms and to conform with the physics of the system more closely.

If we consider motion on the Z and the Y direction, the rigid body effects are not independent this means physically that if the center of mass of the core is moved in Y an Z in translation, so are the PVA's in the same amount so the combination of the masses (I elements) is necessary. Using this approach then we could produce a similar model for the other PVA. is produced using the CAMP-G bond graph editing capabilities. This results in the overall model shown in Fig 8 and used for

computations here. Using this bond graph it is possible to generate the state space form of this system in symbolic form and once physical parameter values are entered, in numerical form. The contribution to the engineer from this approach is that automatically the state space matrices will contain the rigid body and the flexible body dynamics.

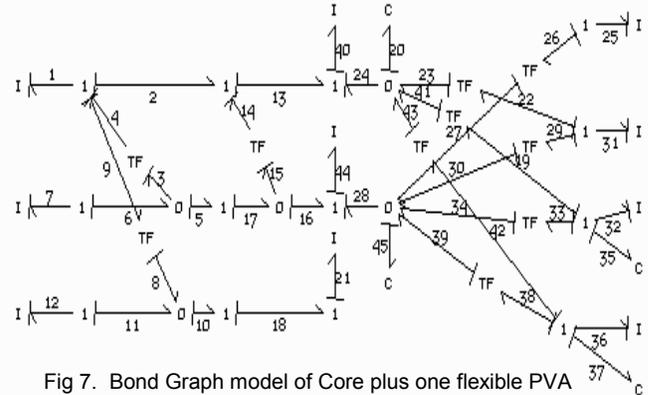


Fig 7. Bond Graph model of Core plus one flexible PVA

ANALYSIS TOOLS and SIMULATION PROCEDURE

The systems researched were analyzed using tools currently in practice for analysis of a space vehicle such as the space station. Full multibody simulation – SOMBAT, Station/Orbiter Multibody Berthing Analysis Tool from Johnson Space Center; for linear analysis – DSAT, Draper Station Analysis Tool from CSDL. Now based on the approach above, using the software tool Computer Aided Modeling Program with Graphical Input (CAMP-G), the objective is to produce the A, B, C, D state matrices at any point of operation or perform the nonlinear simulation.

CAMP-G produces MATLAB .m files. One to initialize parameters (CAMPMOD.M), one to define all differential equations, linear or nonlinear (CAMPGEQU.M) and one to produce the symbolic matrices for the state space form and the Cauchy form of the differential equations (CAMPGSYM.M). Using these M files, CAMP-G interfaces to MATLAB and SIMULINK.

$$dP1 = +Q20/C20 - Q45/C45 / T14 \times 15 - Q45/C45 / T3 \times 4 \\ - Q40/C40 \times T8 \times 9 + Q64/C64 + Q88/C88 \times T58 \times 59 \\ + Q88/C88 \times T46 \times 47 - Q84/C84 \times T48 \times 52 + SE56$$

SYSTEM B MATRIX

- | | |
|---------------------------|----------------------------|
| B(1,:) = [0,0,0]; | B(12,:) = [0,0,0]; |
| B(2,:) = [0,0,0]; | B(13,:) = [0,0,0]; |
| B(3,:) = [0,0,0]; | B(14,:) = [0,0,0]; |
| B(4,:) = [0,0,0]; | B(15,:) = [0,0,0]; |
| B(5,:) = [0,0,0]; | B(16,:) = [0,0,0]; |
| B(6,:) = [0,0,0]; | B(17,:) = [0,0,0]; |
| B(7,:) = [0,0,0]; | B(18,:) = [0,0,0]; |
| B(8,:) = [0,0,0]; | B(19,:) = [0,0,0]; |
| B(9,:) = [+1,0,0]; | B(20,:) = [0,0,0]; |
| B(10,:) = [0,0,0]; | B(21,:) = [0,0,0]; |
| B(11,:) = [0,0,0]; | B(22,:) = [0,+1,0]; |

The output variables are velocities and positions or rates (angular velocities and positions) the computer generated state space matrices are transferred to the state space block in SIMULINK. This now contains a state variable equivalent of the Bond Graph model of the set of flexible bodies as the "PLANT". Once the concept of transformation from a bond graph into state space matrices in MATLAB and SIMULINK then a bridge has been established between bond graph modeling and the rest of the world who understand perfectly well MATLAB/SIMULINK and the state space form. It is this form that DSAT uses. DSAT has been used to test several missions of the space station in linearized points of operation. In the present research the state space representation was generated with the objective of linking it with DSAT and thus it is a way to validate the model since such simulations have produced reliable models for past missions.

DSAT tool is a software package developed for NASA by the Draper Laboratory. The interface is quite practical and graphic, tailored specifically to the space station models. The input in DSAT in the state space form looks like the display shown in Fig 10. It uses the Jang, Jiann-Woei, N. Bedrosian, and E. McCants [3] format. Here the state space block contains the A,B,C,D matrices entered into DSAT with data from SOMBAT or CAMP-G. The system in DSAT has an additional purpose. It implements the control system that controls the space station maneuvers and simulates it together as a close loop system. The control of ISS is accomplished by sensors at specific locations and actuators in the form of jets at fixed locations on the body of the spacecraft, which produce forces and moments along all six degrees of freedom. The contribution of this approach to ISS is that as the plant changes with different configurations, so a new bond graph built upon the previous configuration is possible. Since CAMP-G has a graphics editor to produce new models based on the previous one, then a new plant in the form of a new state space model can be automatically and quickly generated and transferred to DSAT. Since CAMP-G and DSAT both use the MATLAB workspace then a common ground exists to perform the calculations using the state space model. The modeling technique presented here becomes a modeling pre-processor so that the new plants can be transferred to DSAT, indeed to MATLAB and SIMULINK.

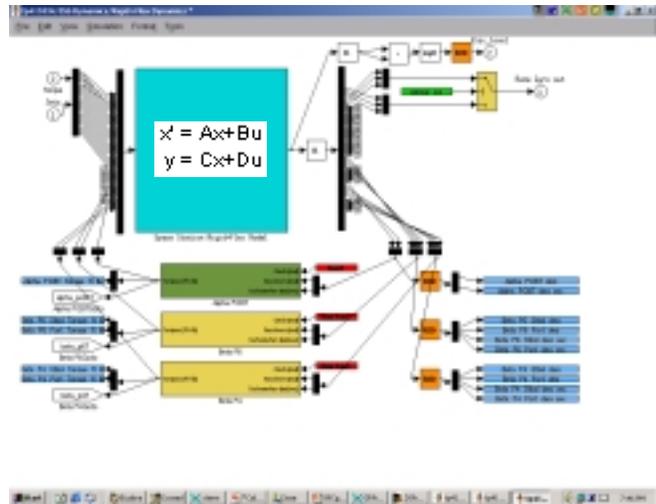


Fig 10. DSAT Space Station State Space model with control

COMPUTER GENERATED TRANSFER FUNCTIONS FROM CAMP-G

DSAT has as its analysis engine behind the MATLAB workspace and uses the SIMULINK graphics display. The computer generated CAMP-G bond graph models direct MATLAB to do the same. Once DSAT has the matrices, whether they came from SOMBAT or CAMP-G the transfer function of the open or close loop systems can be obtained to generate the necessary Bode Plots. Using CAMP-G, it is possible to generate any transfer function for the state variables vector {X} and the output variables (vector {y}), as function of the inputs. In this case this means the displacement or velocity at a particular location where the sensors are located. Since CAMP-G generates the {y} vector of the state space form for all efforts and flows for the entire bond graph model, any desired transfer function relating the outputs to each input can be generated in symbolic form or numeric form. Using the matrices, a vector of transfer functions can be generated for as many transfer functions as desired Granda [9]. Such approach is implemented by CAMP-G and thus produces the desired transfer functions. In this case a transfer function relating the roll jet input and one of the roll gyro output was used to illustrate the method.

Once a SIMULINK block has been established coming from the generation of source .m files and .mdl files in CAMP-G, the whole control systems toolbox from MATLAB is available to conduct simulations in MATLAB or SIMULINK. For this reason using the computer generated state space matrices from the Bond Graph in the DSAT state space model, was considered. The closed loop system including the Russian controller can then be simulated. Using this procedure one can automatically obtain models from a bond graph using CAMP-G and export the models to DSAT or directly in MATLAB or SIMULINK. Therefore, this process can be applied to any bond graph model that represents the International Space Station in its several configurations.

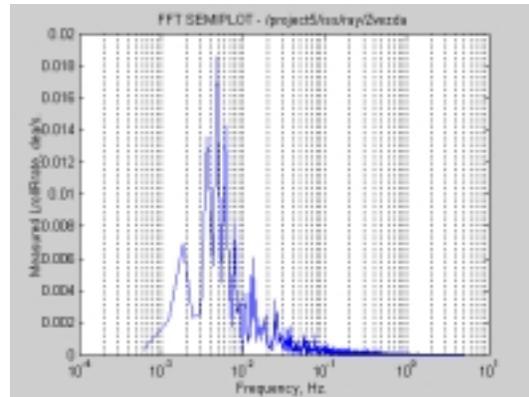
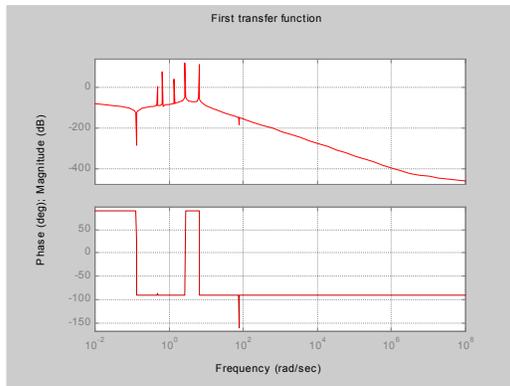


Fig 11. Frequency Response Analysis Bond Graph model (left), Linearized Finite Element model (right)

This kind of analysis was performed on models originally conceived as finite element models and then linearized in state space form. Fig. 11 illustrates the frequency response plots obtained using the bond graph model and that used in SOMBAT. The magnitude and phase corresponds to the rate of the roll gyro. The objective here was to determine the range of important frequencies, which indicate safe ranges of operation. These were used to validate the model and the methodology proposed here. The Bode plots shown in Fig 11 reveal a correlation of frequencies predicted with verified models used in the early stages of ISS. The range of important frequencies is compatible in both models. The CAMP-G computer generated model also allows for the simulation in the time domain with actual nonlinearities.

MODEL CHANGES NEW MISSIONS

One of the challenging research issues is the docking of the Space Shuttle. Considering that the Space Shuttle is a large mass, it is a considerable mass to ignore, the dynamics of the whole system changes. The principles outlined here allow the modeling of a new plant, a set of flexible bodies. Here it is shown how with the addition of inertia elements and junction connections how a new model can be obtained quickly. The base model for the Zvezda configuration can be used to expand to the other set of bodies such as that shown in Fig 12 for Mission 3a. Once a new bond graph is generated following the procedure outlined here, a new model is generated and the system matrices produced in a matter of minutes. Such new configuration has three rigid bodies, 1, 2, 3 (space shuttle) and four PVA arrays A, B, C, and D. This is a subsequent mission for Zvezda for which a new bond graph model was generated in CAMP-G. It is shown in Figure 13. A new bond graph based on the procedure outlined here generates a new "plant" model whose state space model can be delivered to DSAT for a close loop analysis with its controller or analyzed in MATLAB as an open loop system using either the computer generated state space matrices or transfer functions.

The process applied to these dimensional models differs only on the complexity of the Bond Graph but the computer-generated approach is the same. The addition of new bodies or of electromechanical elements such as motors or other kind of actuators can be included in an integrated model. Thus in modeling systems that involve several different forms of energy, considering even the dynamics of sensors and actuators are possible. Granda [15] has demonstrated how such implementation is generalized to Mechatronics systems, which not only are composed of sensors, actuators but of control systems. What one may add to that with this paper is the ability to model and simulate multi energy system with rigid and flexible multi bodies. The ability to model and simulate multi-energy systems using bond

graphs has been demonstrated to be one of the most valuable contributions in the field of modeling and simulation.

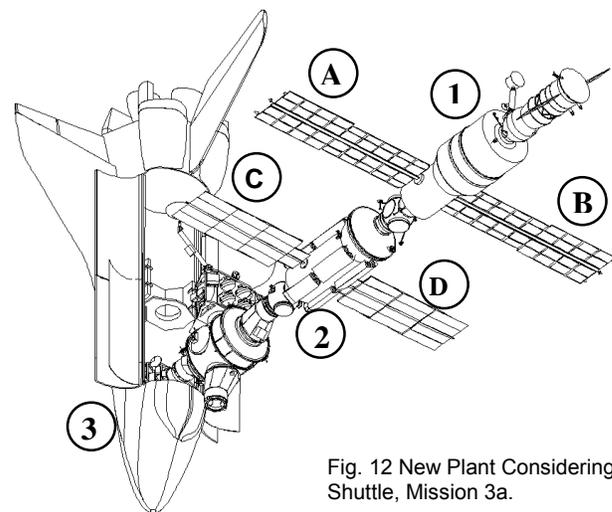


Fig. 12 New Plant Considering Shuttle, Mission 3a.

CONCLUSIONS

This paper has demonstrated the mathematical relationships and the methods for modeling flexible multi-body systems as they relate to the bond graph methodology and to the state space methods. Computer automation of the process has been studied and compared to traditional methods of modeling and computation. Since CAMP-G produces a state space representation of systems modeled in bond graphs, this research has demonstrated the relation to mathematical foundations of classical methods commonly used and establishes the links to the Bond Graph method.

The research presented here bridges two technologies: classical block diagram methods and bond graphs. Modeling motion of rigid bodies in three dimensions involves a mathematical representation of Euler's equations. Modeling dynamics of flexible bodies involves solution of time dependent partial differential equations. This paper shows that both are possible using the bond graph technology. In this case the original models start in the finite element method and the intermediate step is to linearize them at an operating point. In so doing, the state space form becomes the representation of a particular configuration and operating point so that the model is analyzed using frequency response techniques.

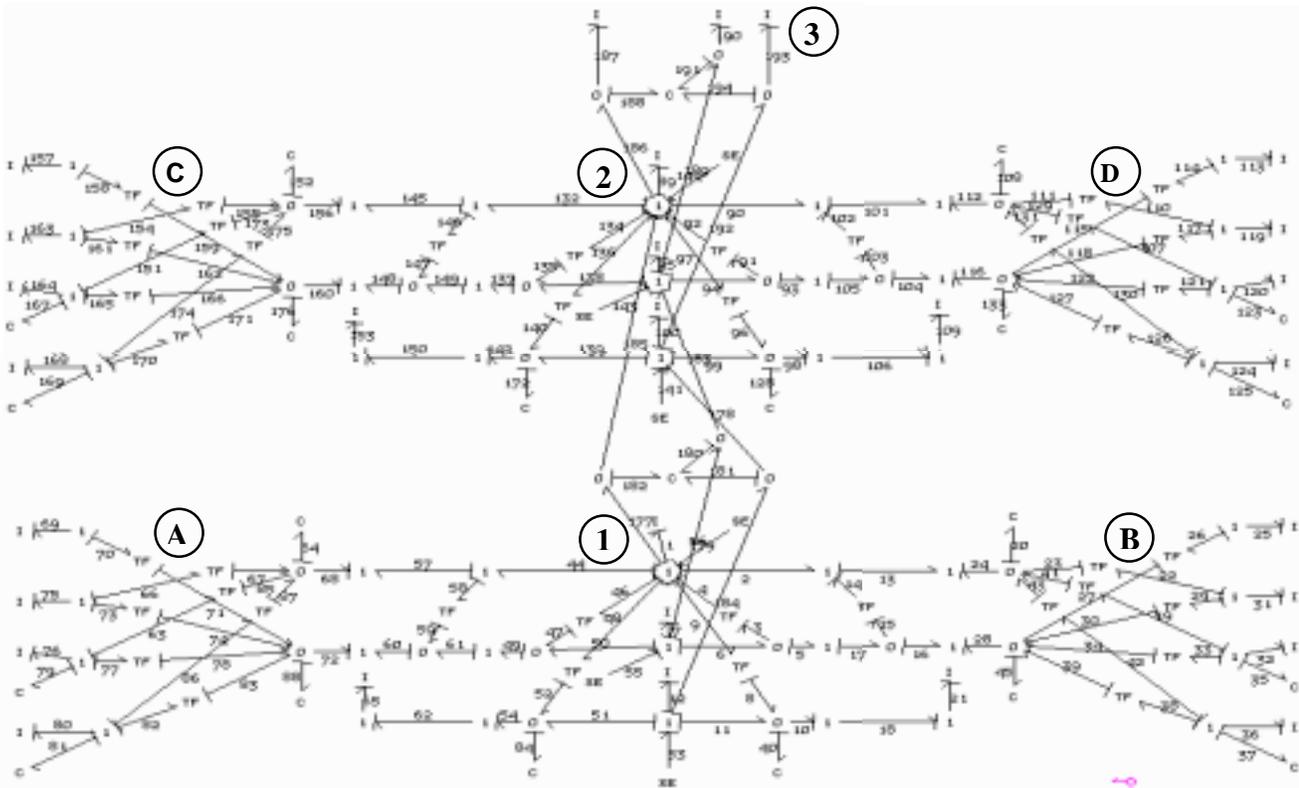


Fig 13 Zvezda, Service Module and Space Shuttle CAMP-G Bond Graph Model Mission 3a

The paper demonstrates a common ground for combining current research tools of analysis such as DSAT, SOMBAT with MATLAB and SIMULINK toolboxes with the emerging bond graph technology.

A goal of this approach is to simplify the modeling of rigid and flexible multi-bodies by introducing bond graphs, which retain the significant dynamic information of the rigid and flexible body modes. The technique demonstrated here is a process to automate the modeling and simulation by using software to generate the differential equations, the state space form and the transfer functions. Automated modeling presented here allows the generation of the nonlinear model since all is generated in symbolic form.

This research demonstrates how these models can evolve into more complex "plants"; an approach particularly suited for changing configurations such is the case with ISS. For example, the addition of a new section or the docking of the Space Shuttle induces a dynamic change that produces a new model. Using the bond graph technique allows for modification of the model quickly and efficiently yet using the existing one as basis and adding new elements to it just as it is in reality built in space. Once that happens the generation of the new model is achieved following the automated procedure presented here.

REFERENCES

[1] Singh, R. P., R.J. VanderVoort, and P. W. Likens: Dynamics of Flexible Bodies in Tree Topology. *AIAA J. Guidance, Control, and Dynamics*, Vol. 8, No. 3, September-October 1985, pp. 584-590.
 [2] Kane, Thomas and D. A. Levinson. Formulation of Equations of Motion for Complex Spacecraft. *AIAA J. Guidance, Control, and Dynamics*, Vol. 3, No. 2, March-April 1980, pp. 99-112.
 [3] Jang, Jiann-Woei, N. Bedrossian, and E. McCants: DSAT – A Modular Simulation Development & Analysis Tool:

[4] Catherine A. Jorgensen, Editor: International Space Station Evolution Data Book Revision A, NASA/SP-2000-6109/Vol. 1, Rev. 1, October 2000.
 [5] Karnopp D, Margolis D, and Rosenberg, R., "Systems Dynamics a Unified Approach," Wiley and Sons, New York. January 2000
 [6] Margolis S., Karnopp D, Bond Graphs for Flexible Multibody Systems. *Transactions of the ASME*. Vol 101. March 1979.
 [7] Granda J. J. "Computer Generation of Physical System Differential Equations using Bond Graphs." *Journal of the Franklin Institute*, January/February Issue, 1985
 [8] Granda J., Reus J. "New developments in Bond Graph Modeling Software Tools: The computer Aided Modeling Program CAMP-G and MATLAB". The IEEE International Conference on Systems, man, and Cybernetics. Orlando, Fla. October 1997.
 [9] Granda J. " Computer Generated Transfer Functions CAMP-G: Interface to MATLAB and SIMULINK" *Proceedings of the International Conference on Bond Graph Modeling and Simulation ICBGM'99*. San Francisco, Ca. January 1999.
 [10] Granda J., " Computer Generated Block Diagrams from Bond Graph Models CAMP-G as a Tool Box for SIMULINK" *Proceedings of the International Conference on Bond Graph Modeling and Simulation ICBGM'2001 Phoenix, Arizona*. January 2001
 [11] Segerlind L: *Applied Finite Element Analysis*. Wiley, 1984
 [12] Granda, Kong Time Dependent Computational Relations Between Finite Elements And Bond Graph Modeling. *ICBGM'93 Proceedings*. La Jolla, CA 1993.
 [13] Granda, Kong Pseudo Bond Graph Models and Finite Element Models of Transient Heat Transfer Problems. *ICBGM'93 Proceedings*. La Jolla, CA 1993.
 [14] Meirovitch, L.: *Dynamics and Control of Structures*. John Wiley & Sons, New York, 1990, pp 269-312.
 [15] Granda J. The Role of Bond Graph Modeling and Simulation in Mechatronics Systems. *Journal of Mechatronics* 12 (2002) 1271-1295.