Maple Models Motions of Robot Arm for the ISS

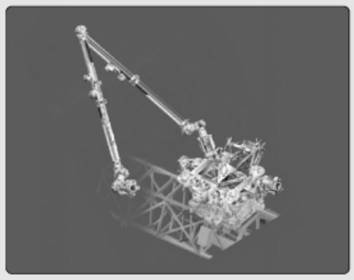
Canada's contribution to the International Space Station (ISS) is the Mobile Servicing System (MSS), a complex manipulator that includes robot "arms" that can pick up and manipulate everything from delicate objects to large payloads. Because it is designed for use in the weightlessness of space the manipulator cannot be tested effectively on Earth. Therefore, to ensure reliability and examine its entire range of tasks and assignments, the Canadian Space Agency (CSA) tests the manipulator using mathematical models and simulators in software supplied by Waterloo Maple.

International Space Station Animation Still Image (Courtesy Canadian Space Agency 2001)

HIGH-FLYING HARDWARE

The ISS is the largest international scientific program ever, being built jointly by the United States, Canada, Russia, Japan, and 11 European countries. The size of a football field when fully assembled, it will weigh close to 400 metric tons and generate 110kW of power with its solar arrays. The station will support a permanent crew of seven astronauts. More than 50 shuttle missions will be needed to transport and assemble the station.

At the heart of the assembly operation is Canada's MSS, being built and tested at CSA's facilities in Saint-Hubert, Quebec. The MSS will be used to unload equipment from the shuttles, move heavy objects, help assemble the space station, and maintain it afterwards. Dr. Jean-Claude Piedboeuf, manager of robotics at CSA, describes the MSS: "The manipulator includes a main arm (the Space Station Remote Manipulator System, or SSRMS) and a smaller manipulator with two arms (the Special Purpose Dexterous Manipulator, or SPDM). The large arm is 17 meters long and very flexible. The smaller manipulator has two 3.5-meter arms with exceptional dexterity that allows very fine motion for delicate tasks."



Computer model of the robot arm (Courtesy Canadian Space Agency 2001)

Each arm has seven actuators, and the entire assembly has 22 rigid degrees of freedom and more than 30 flexible ones.

In a typical task, the SSRMS will move the SPDM to a location where maintenance needs to be performed. One arm of the SPDM will grasp a stabilization point, creating a closed kinematic loop. The other arm will delicately remove and replace a part on the space station, a task involving contact dynamics. Testing such a task could be a nightmare, but the CSA has had a great deal of experience with manipulators ever since it built a robot arm for the first space shuttle. "Over the past 20 years, CSA has developed modeling and simulation tools for offline and real-time simulation of space manipulators," says Dr. Piedboeuf. "For the R&D, we've developed our own general purpose program, called SYMOFROS, to do flexible dynamic modeling. The system uses Maple's symbolic modeling and C-code generator software."

For the MSS, Dr. Piedboeuf's group has to verify that every operation will actually work. "We have to perform Task Verification to make sure that every task will execute properly in space. The actual hardware is so light that it cannot support its own weight here on Earth. So we have to simulate and emulate everything in software."

To verify contact dynamics actions—such as actually inserting a part into a receptacle—CSA uses an earth-bound robot that has been modified to simulate actions of the SPDM. Math models developed using SYMOFROS and Maple software are downloaded to the actual robot controllers, which carry out the task.

MAKING MODELS IN MAPLE USING SYMOFROS

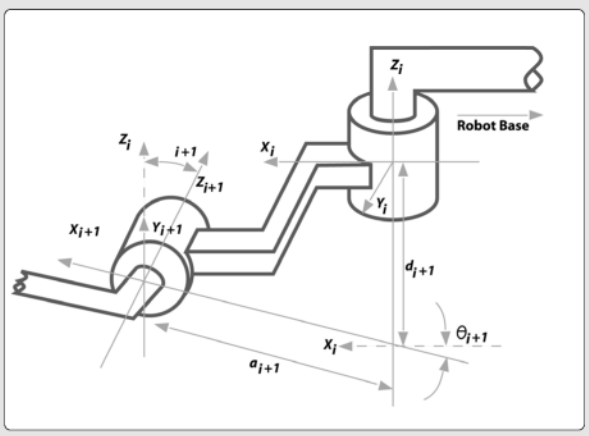
Running a simulation of a space manipulator is a very complex process in which SYMOFROS uses Maple, MATLAB, and Simulink software packages. First, every mechanism in the manipulator must be defined as an object, with information describing all the forces associated with the 48 object's motion or tasks. This includes rotation and position matrices, center of mass, inertia, external torque and forces acting on it, gyroscopic effects, beam deformations, internal damping, motor torque, elastic torque, and so on.

Next, an operator must construct a graphical model using a MATLAB-Simulink program to describe the robot system's topology. The operator drags and drops object blocks from a library, links them together, and then downloads the result to the Maple Math Engine.

"Maple takes the object information files and generates a model in symbolic form," says Dr. Piedboeuf. "Once Maple has processed the information related to the model's description, it generates C code for conducting the simulation."

The dynamics equations are built following Jourdain's principle, which is a variational method in which constraint forces are eliminated. The Maple part of SYMOFROS obtains kinematics and dynamics recursively and models the flexible beams using Euler-Bernoulli approximations. By consistently eliminating high-order terms, it generates equations of motion that are exact to the first order.

When the Maple software completes its symbolic linearization of the model and generates the C functions that will be needed for simulation and control, it then optimizes the C code. The generated code can now be compiled and loaded into MATLAB and Simulink for execution.



Math variables for robot arm models.

"Without the Maple software, we would have to spend weeks generating the equations of motion for every experiment," says Dr. Piedboeuf. "Then, the chances that we did it right would basically be near zero. There always would be a mistake somewhere. It is very difficult to set up a dynamic motion model by hand."

Measuring the benefits of the Maple software is difficult because the task could not have been done any other way. Fortunately, now that the SYMOFROS system is running, the R&D Department of CSA can use it for a wide variety of tests. "It's a useful tool," says Dr. Piedboeuf. "We have been using it for many other applications, because we have several other robots and manipulators in development here. If you use Maple's software in just one application, it saves time and money when compared with the cost of generating code by hand. But the real value is that we can use everything we've developed for all our other projects."

He adds, "Our goal is to allow our users to generate the right kind of code, quickly and easily. When you simulate a system, it's not just one equation of motion you need. You need many equations to analyze a system and to be able to link the model into a control system. With Maple, we can generate those equations automatically for a user."

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