Using ADAMS to Model Cable Driven Hyper-Redundant Flexible Manipulators

Stefan Slagowski
GreyPilgrim, Inc.
Rockville, Maryland

Alvin Potter
Advanced Simulation Technology, Inc.
Glen Mills, Pennsylvania

Introduction

This paper outlines the current state of the virtual prototyping program using ADAMS under development at GreyPilgrim Incorporated. This program is being developed in order to provide analysis in the mechanical design of cable driven hyper-redundant flexible manipulators, referred to as EMMAs (Easily Manipulated Mechanical Arms). A diagram of a typical EMMA manipulator can be seen in Figure 1 below.

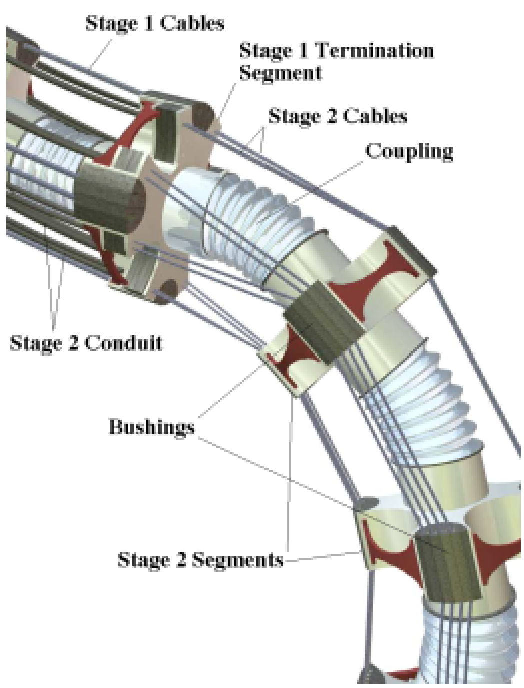

Figure 1: EMMA Manipulator

An EMMA manipulator is constructed from rigid segments that are connected with flexible couplings. Each manipulator is composed of individually controlled stages that consist of a series of the segments and couplings. Typically, a stage consists of three segments and three couplings. Each stage is actuated by sets of cables that are routed through the stage by the segments and terminate at the final segment of the stage. Three or four sets of cables can be used for actuation, with each set equally spaced around the circumference of the manipulator. The stage is bent into curves by tensioning the cables, the direction of the curve depending on relative lengths of the cable sets. The overall manipulator is made up off several stages, allowing the manipulator to form various compound curves.

The pictures in Figure 2 show a manipulator in operation. The manipulator is composed of three stages each with three couplings and segments with a total length of 15 feet. Past manipulators have been constructed with lengths ranging from 1 foot to 30 feet. The manipulator shown in Figure 2 is actuated with hydraulic cylinders that are located at the rear of the support structure. Forces on the cylinders can reach up to 10,000 lbf. in order to bend the manipulator in tight curves.

Figure 2: EMMA Manipulator in Operation

Problem Definition

Although past manipulators have been successfully operated for demonstration purposes, several issues remain with the past designs and design methodologies. These issues need to be addressed in order to design and implement a robust EMMA manipulator for commercial use that meets the specifications of a given application.

The first issue is the method of determining design variables of the manipulator so that it can meet the specifications of the application it is designed for. Variables include coupling material, coupling dimensions, cable routing, and the dimensions of the rigid components of the manipulator. To this point, these have been determined through trial and error, experimentation, and best guesses with minimal use of predictive analysis. This leads to higher costs due to longer development times and a high dependence on physical prototypes. This method also does not lead to the most optimal designs. Design improvements that can be made include decreasing the forces required to bend the manipulator and increasing the maximum lifting capacity.

The second issue is the system reliability of the manipulators and manipulator deployment hardware during operation. Many of the failures of previous manipulators have been mechanical in nature. In order to compensate for undetermined loads, components are typically over designed. If more accurate loading conditions can be used in the structural design of mechanical components, the overall system will be lighter and less costly.

Both of these issues are being addressed by using ADAMS to create dynamic models of the manipulator. The goal of the virtual prototyping program is to provide engineers a tool to create a complete, accurate model of the manipulator to be used early in the design process. The model provides a baseline that an engineer can change in order to verify the manipulator design's functionality and to optimize its performance.

Component Models and System Integration

Currently, models of individual dynamic components are being developed and verified through physical testing. Component models will be integrated into an overall model of a manipulator once they have been verified. Components are modeled on an individual basis in order to quantify and minimize the model errors before integration into a system level model. System integration will be performed using ADAMS/View macros to integrate the component models into an overall system. A baseline set of macros has been generated that combines the current models of the components into a complete manipulator. These macros will be changed to reflect the improvement of the component models. Macros will also be created when new components are added to the design of the EMMA manipulators.

The dynamic components are broken down into couplings, cables, and actuation. Accurate models of each of these components are essential before an overall manipulator system model can be used for design purposes. The current states of the component level models and system integration are outlined below.

Couplings

The couplings provide the flexibility of the system and allow the manipulator to bend in continuous curves. Couplings are constructed from polyurethane and have a round cross-sectional area that allow them to bend in all directions. A representation of a typical coupling can be seen in Figure 3.

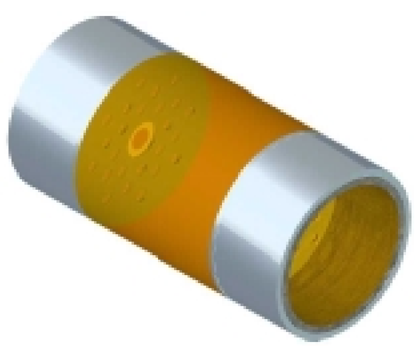

Figure 3: EMMA Coupling

Because of the material properties of the polyurethane, the couplings provide a challenge in defining a viable dynamic model. Polyurethane exhibits hysteresis, non-linear stress-strain characteristics, compression set, and temperature dependency.

Two models are being developed for the couplings in ADAMS. The first model breaks the coupling into a series of ADAMS *beam* elements as seen in Figure 4.

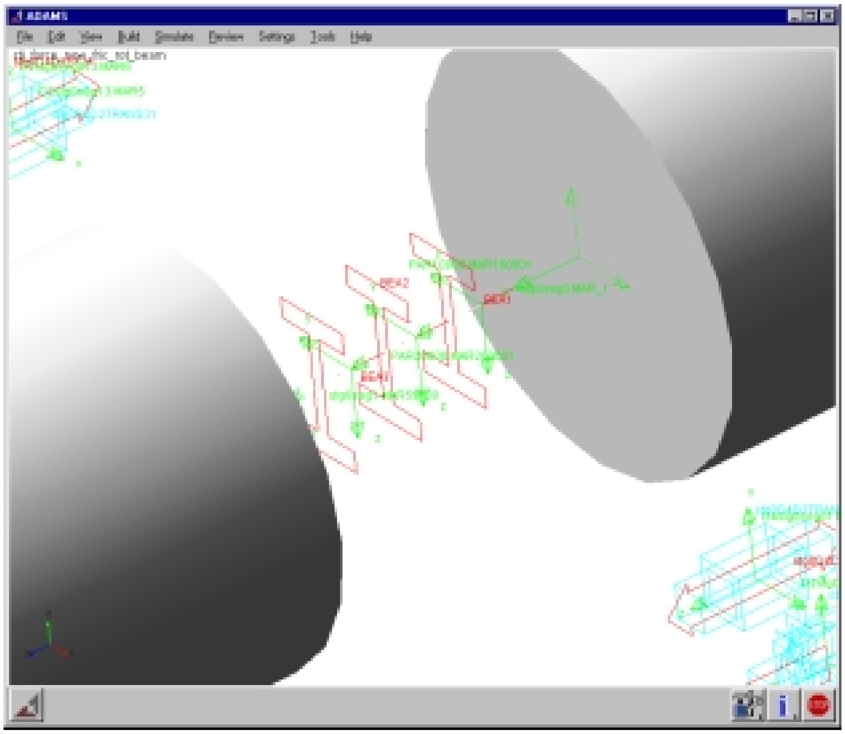

Figure 4: ADAMS Beam Element Representation of Coupling

Multiple *beam* elements are used in order to achieve an accurate portrayal of the high deflection that the couplings are subjected to. The accuracy of the beam model depends on the materials stress-strain characteristics. If at the estimated strain regions, the stress-strain curve of a material is linear and the compressive modulus is the same as the tensile modulus, the coupling can be modeled as a beam. Hysteresis is modeled by adjusting the damping characteristics of the beam elements. The damping characteristics will be determined from the relationship between the storage and loss modulus of the material. Further work is necessary in order to map the storage and loss modulus relationship to the correct value of the damping terms in the *beam* elements.

The second model being developed will utilize results from finite element analysis (FEA) to determine the stiffness of the coupling under loading. Results from FEA will be used if the stress-strain relationship is non-linear in the estimated strain regions. Results from FEA can be incorporated into a *field* statement and non-linear terms can be implemented using user defined sub routines. Whether the additional accuracy of the coupling models derived from FEA is worth the additional cost is yet to be determined. The predicted results from the beam models may provide the necessary accuracy at a much lower cost in both time and money.

Compression set will not be incorporated into the coupling models. It will be assumed that the couplings return to the same unloaded state after being loaded. This assumption is based on the polyurethane material selection. Polyurethane selected for coupling construction will exhibit minimal compression set characteristics. Effects of temperature will be modeled by adjusting the stiffness and damping characteristics of the coupling models.

Cables

Because there are no predefined cable elements in the ADAMS, a majority of the initial work was defining how the cables would be represented in the models of the EMMA manipulators. In developing the analytical cable representations for the ADAMS model, the primary objective was to accurately model the cable reaction forces, bushing loads, and cable stretch.

The cables are modeled as a series of stiff springs. To calculate the actual deformation in a cable due to a given load, the stiffness of the cable needs to be determined. With linear elastic material properties, the gross stiffness (k) of a cable can be determine from the following linear relation:

$$k = \frac{A'E}{L}$$

Where A' is the effective cross-sectional area of the cable, E is the Elastic modulus of cable, and L is the length of the cable being considered. The simple relation defines gross deformation or cable stretch $(Disp)$:

$$Disp = \frac{F}{k}$$

Where F is the tensile load in the cable.

Initially, cables in a cable set are not modeled individually. One cable representation was used to represent all cables of a set. With only one cable at a station, the moment arm assigned to the cable is the average based on the moment arms of all the cables in the set. This assumption is depicted in Figure 5.

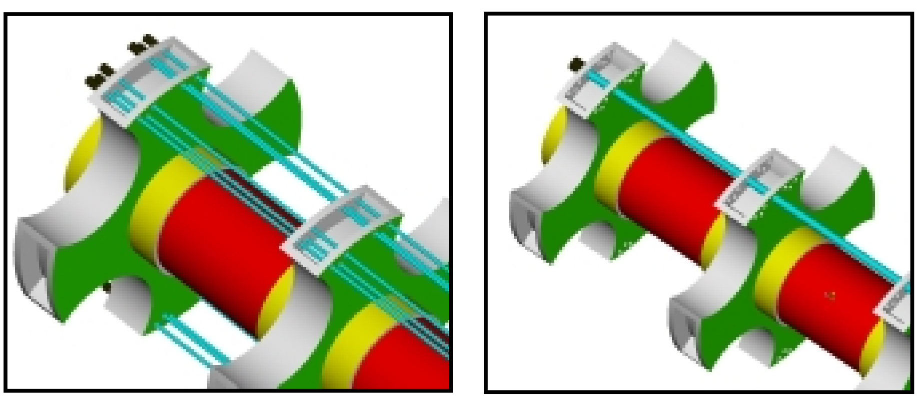

Figure 5: Single Cable Representation

Figure 6 shows a typical configuration for a manipulator stage while bending. Only the top and bottom cables are shown for clarity. Balloon locations A through F represent cable pass-though-bushing locations. The active cable region refers to the cable that runs between the segments. As the segments are bent, the cable length in the active region will increase or decrease depending on the direction of the bend. The coupling region refers to the portion of cable inside the pass-through bushings. The coupling region distance is fixed and stays straight based on the segment geometry. The section of cable labeled ADAMS cable region refers to the portion of cable that is considered by each force function developed within ADAMS. Separate force functions are developed for each set of cables. Cable that is added or removed from the active regions is added or removed to the ADAMS drive region, keeping the total non-stretched cable length constant. Catenary cable bending is not considered due to the short lengths and high tensile loads. Therefore, the total length of cable for any given run can be defined by the summation of cable lengths between the bushing locations.

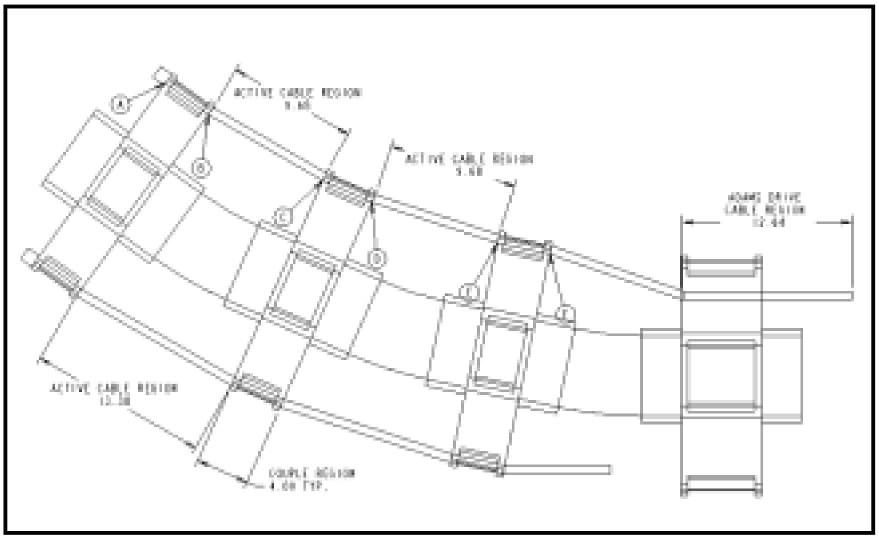

Figure 6: Cable Routing Through Segments

From an analytical perspective, cables represent tensile force vectors with a given magnitude and direction. Both magnitude and direction of the force is important to consider in the ADAMS modeling approach. For the arm model, the magnitude of the cable force is defined by the systems weight and force required to bend the couplings. Coupling bending is accomplished by pulling on the last segment in a stage. The cable reaction loads imparted on the termination segment and cable routing bushings causes the arm to bend. The direction of the cable force is defined by the geometric routing of the cable through the structure. As the arms bends the cable orientations continuously change to conform to the new configuration.

In order to change the cable force direction as the manipulator was bent, it was required to use rigid dummy parts in the ADAMS model. At each cable bushing location on the opposite sides of the active cable region, a dummy part D1 is created and attached to the segment rigid body via a spherical joint. A second dummy part D2 is attached to the D1 part with a translational joint. Two dummy parts are created at each cable bushing location where the cables enter and exit the bushing. The spherical joints allow the frustums on adjacent segments to always keep a direct line-of-sight. This straight line represents the active cable region. Therefore, the cable line-of-sight is defined by adjacent segment bushing orientations. To achieve this line-of-sight requirement another translational joint is added that connects the two dummy parts that are attached to the spherical joints. This joint provides the proper cable orientation.

Figure 7 shows the representation of a cable in the active cable region. The red and green spheres, which are attached to the D1 parts, represent the spherical joints. The magenta frustums, which are attached to the D2 parts, represent the translational joints. On a given segment, the orientation of the proximal bushings will be different from the distal bushings when the manipulator is bending.

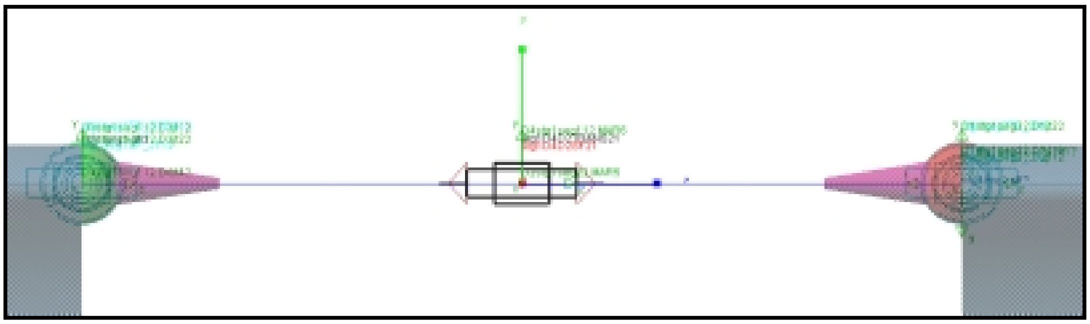

Figure 7: ADAMS Cable Representation in Active Cable Region

To track the cable travel, couplers were added to the cables of adjoining active cable regions. The coupler joint controls the magnitude of linear motion in the region defined earlier as the couple region. The motion monitored is total motion and is independent of direction. If one inch of cable is pulled out of one side of a segment, 1 inch of cable must be pulled in on the other side of the segment.

The stiffness of the cable is represented with a *sforce* and acts between the markers that define the translational joint in the active cable regions. The *sforce* is a function of the distance between the two markers and is defined by the stiffness equation shown above. The *sforce* can be seen graphically in Figure 7.

Friction loss of the cable over the bushings is modeled by incorporating addition *sforce* statements into the cable model. The frictional forces act in the opposite direction of the stiffness *sforce*, effectively decreasing the tension in the cable. Although preliminary models of friction loss have been developed, they have not been verified through physical testing. The accuracy of the friction loss models is of great importance to the behavior of the model because of the modeling error that would accumulate each time a cable passes through a bushing.

Actuation

The actuation system will be modeled last after the mechanical components have been successfully integrated into the manipulator model. The actuation is selected based on the force required to bend the arm. For smaller systems, manual actuation or electric motors can be used to provide the necessary force on the cables. For larger manipulators that require high levels of force to actuate, hydraulic cylinders are used.

In order to model the hydraulic circuits used to control the manipulators, ADAMS/Hydraulics will be utilized. ADAMS/Hydraulics provides the ability to expand the analysis of the manipulator design to the hydraulic actuation without the need generate hydraulic component models from the ground up.

With the inclusion of the ADAMS/Hydraulics models, the design analysis of the manipulator will be expanded to controller design of the larger EMMAs. Controller analyis is a longer term project and falls outside of the scope of this paper. However, hydraulics models will be used to determine proper sizing of hydraulic cylinders and hydraulic circuit design in simple simulations of worst case loading scenarios.

System Integration

Because EMMA manipulators share many of the basic characteristics from design to design, it was desired to have an automated model generator developed. An interactive graphical modeling procedure via ADAMS/View macros was created to aid in the development of a complete ADAMS model of the system. The use of these macros enables a user to development a complete model without needing to know many ADAMS modeling details. Most of the repetitive modeling requirements are addressed within the macros.

Separate macros were developed for creating the segments, cables and couplings. The user defines critical modeling parameters through interactive input panels. As new components are implemented in the design of the manipulators, new macros will be generated to include these. The macros will also be expanded to parameterize the model as it is being generated. Parameterization to allow the engineer to change the routing of the cables, dimensions and material of the coupling, and the dimensions of the rigid elements of the manipulator.

Figure 8 shows a complete manipulator model generated using the macros. The model is based on the manipulator that is shown in Figure 2. The gross motion of the model matches that of the demonstration arm in operation.

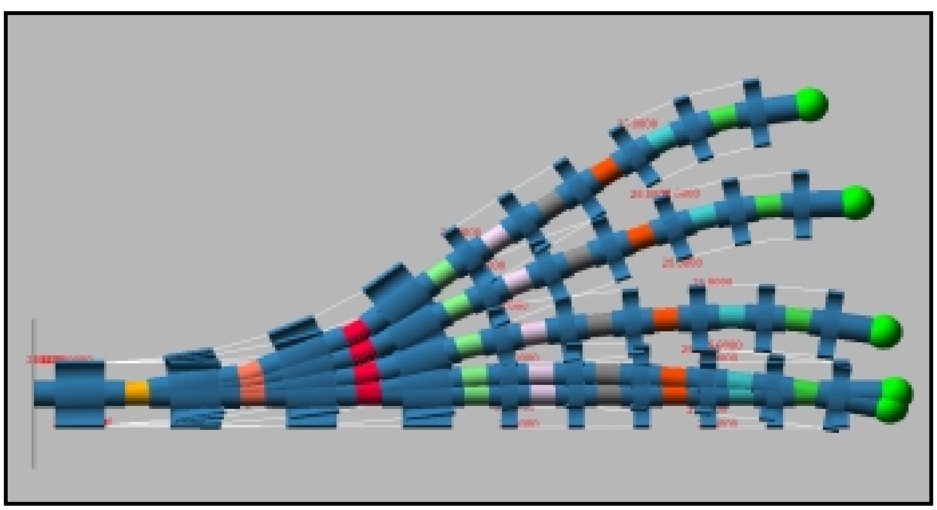

Figure 8: Macro Generated EMMA Model

Summary

Although many of the initial models still need to be verified with test results, the ADAMS work to this point has yielded promising results. Currently, the ADAMS models of the EMMA manipulators correctly predict the gross motion of the physical hardware. In order to determine the sources of error, component models need to be broken out and verified independently of the overall system. In order to verify the component models, test equipment is being manufactured and updated in order to test the individual components of the manipulators. Once a sufficient level of empirical data is gathered, the current baseline models will be updated and verified.

System models will then be verified against manipulators in operation. These include several test jigs and manipulators being designed and manufactured for current contracts. Once the confidence level in the accuracy of the models is sufficient, the tool will be used in the design of future EMMA manipulators.