Real-time Simulation of Cable-Based Robotic End Effectors

Siamak Arbatani[1], József Kövecses[1], Marek Teichmann[2]

[1] Department of Mechanical Engineering
Centre for Intelligent Machines
McGill University
817 Sherbrooke St. West
Montréal, QC, H3A 0C3, Canada
[siamak.arbatani, jozsef.kovecses]@mcgill.ca

[2] CMLabs Simulations
645 Wellington
Montréal, QC, H3C 1T2, Canada
marek@cm-labs.com

EXTENDED ABSTRACT

1 Introduction

The Space Station Remote Manipulator System (SSRMS) known as Canadarm2 has two so-called Latching End Effectors (LEEs) one at each end; these are capable of handling large payloads. A LEE has 3 snare cables to capture the grapple fixture shaft. Grapple fixtures provide a secure connection between spacecraft or other objects and International Space Station (ISS). The main mechanism and photos of LEE along with grapple fixture are illustrated in Fig. 1. The 3 snare cables are connected to co-axial cylinders. First, snare cables partially wrap around the pin (grappling maneuver) and then the pin is pulled for latching (latching maneuver).

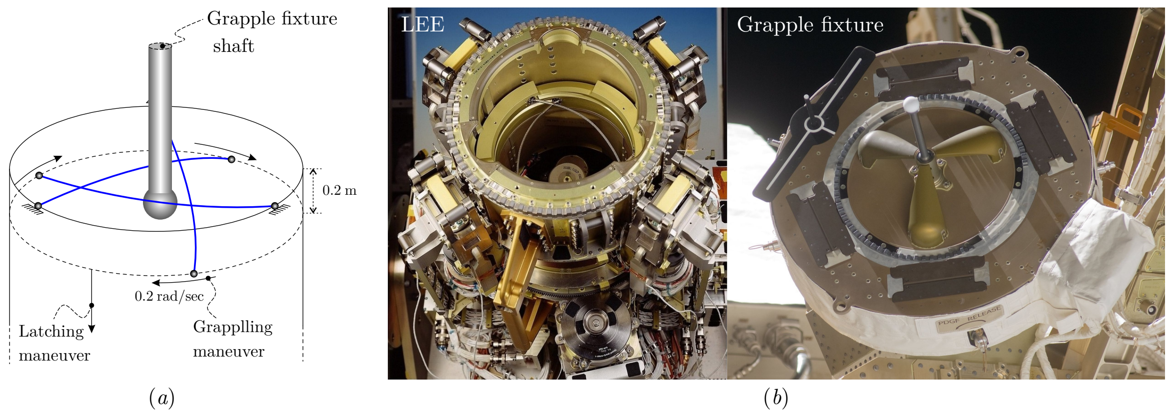

Figure 1: (*a*) Schematic of grapple fixture and LEE, and (*b*) Canadarm2 Latching End Effector (LEE) and Power and Data Grapple Fixture (PDGF) – Photo: NASA/CSA.

Simulation of the LEE is challenging due to different elements including high tension in the cables while they contact each other and the payload. Due to the high tension so-called contact tunneling can be a significant problem during the grappling and latching. Capturing the large and complex deformations of the cables and their interactions with payload and each other requires a proper formulation and a stable time stepper.
In this work, we employ the gradient deficient Absolute Nodal Coordinate Formulation (ANCF) beam elements to model the cables of the LEE. The contact/collision geometries of these elements are represented by capsule decomposition. A fast and stable first-order method is utilized for the simulation of the flexible cables and their interaction with each other and the other elements of the end effector and the payload [1]. To demonstrate the results the grapple pin is connected to a 20,000 kg payload and captured and pulled by cable-based end effector mechanism. Contacts between pin and cables as well as contacts of cables with each other are modelled based on unilateral constraints. Real-time and stable solution is achieved for this model and operation.

2 Cable modelling method and contact handling

Each of the snare cables is modelled using 10 ANCF cable elements. ANCF based elements can represent arbitrarily large deformations. These elements are very suitable for contact modelling, as they can function well with first-order time stepping due to properties such as constant mass matrix. Each cable element is defined by two sets of nodal coordinates containing position and gradient coordinates. Cubic interpolation is used for this element. The terms of the dynamic equations are determined as described in [2].
Fixed and sliding position constraints are employed to achieve the grappling and latching maneuvers in two steps. First step involves fixed constraints at one end of each cable and circular sliding constraints at the other end. After achieving the desired grappling, all the constraints are replaced with linearly sliding constraints to perform the latching maneuver.

Collision geometry of the cable elements are approximated by capsules. Capsules as collision geometries have the advantage of having overlapping end points, eliminating the likelihood of gaps in the spherical decomposition under high tension. After broad phase collision filtering, capsule-capsule collision detection is conducted. The resulting collision points on the capsules are projected onto the corresponding cable element to determine the local collision coordinates. The computed contact Jacobian is then incorporated into the dynamics formulation.

3 Time stepping method

A novel first-order integration method for the gradient deficient beam elements based on the absolute nodal coordinate formulation is presented in [1]. The method involves splitting the elastic potential using the quadrature points and treating the forces as relaxed constraints in the compliant constraints formalism. The integration method has excellent stability, good scalability and can be solved efficiently with a single linear solve. We can write the dynamics equations in a compact from as

$$\mathbf{M}\ddot{\mathbf{q}} = \mathbf{f}_{\text{int}} + \mathbf{f}_{\text{oth}} \tag{1}$$

where $\mathbf{f}_{\text{int}}$ and $\mathbf{f}_{\text{oth}}$ represent the generalized internal forces and all other forces, respectively, $\mathbf{M}$ is the mass matrix, and $\ddot{\mathbf{q}}$ indicates the generalized accelerations. Considering this and performing time discretization, the form for the first-order time stepping can be written as [1]:

$$\begin{bmatrix} \mathbf{M} & -\mathbf{J}_{\kappa}^{\mathrm{T}} & -\mathbf{J}_{\varepsilon}^{\mathrm{T}} & -\mathbf{J}_{\text{cons}}^{\mathrm{T}} \\ \mathbf{J}_{\kappa} & \mathbf{C}_{\kappa}/h^2 & \mathbf{0} & \mathbf{0} \\ \mathbf{J}_{\varepsilon} & \mathbf{0} & \mathbf{C}_{\varepsilon}/h^2 & \mathbf{0} \\ \mathbf{J}_{\text{cons}} & \mathbf{0} & \mathbf{0} & \mathbf{0} \end{bmatrix} \begin{bmatrix} \dot{\mathbf{q}}^{+} \\ h\boldsymbol{\lambda}_{\kappa} \\ h\boldsymbol{\lambda}_{\varepsilon} \\ h\boldsymbol{\lambda}_{\text{cons}} \end{bmatrix} = \begin{bmatrix} \mathbf{M}\dot{\mathbf{q}}^{-} + h\mathbf{f}_{\text{ext}} \\ -\boldsymbol{\phi}_{\kappa}/h \\ -\boldsymbol{\phi}_{\varepsilon}/h \\ -\boldsymbol{\phi}_{\text{cons}}/h \end{bmatrix} \tag{2}$$

where $\mathbf{J}_{\kappa}$ and $\mathbf{J}_{\varepsilon}$ are blocks with rows of derivatives of axial and bending strains with respect to element coordinates at Gauss quadrature nodes, $\mathbf{C}_{\kappa}$ and $\mathbf{C}_{\varepsilon}$ are constant diagonal matrices of constitutive properties of the elements, h is the time step, $\boldsymbol{\phi}_{\kappa}$ and $\boldsymbol{\phi}_{\varepsilon}$ represent strains at Gauss quadrature nodes and $\mathbf{J}_{\text{cons}}$ is the constraint Jacobian. It should be noted that the system is comprised of the rigid body which represents the payload and grapple pin as well as the system of 3 snare cables. Fixed and sliding constraints in addition to the contact constraints are all encapsulated in $\mathbf{J}_{\text{cons}}$.

4 Results

This simulation is implemented in C++ using Eigen v3 library. The solution is obtained with the method of principal pivoting to ensure complementarity conditions at the contact constraints. Cholesky factorization from the Eigen library is used to factor the equations for the basic variables. Stable and real-time solutions are achieved with a constant time step of $h = 0.001$ s. Magnitudes of the constraint forces at the ends of each cable are plotted in Fig. 2 that also shows a snapshot of the animation of the dynamic simulation.

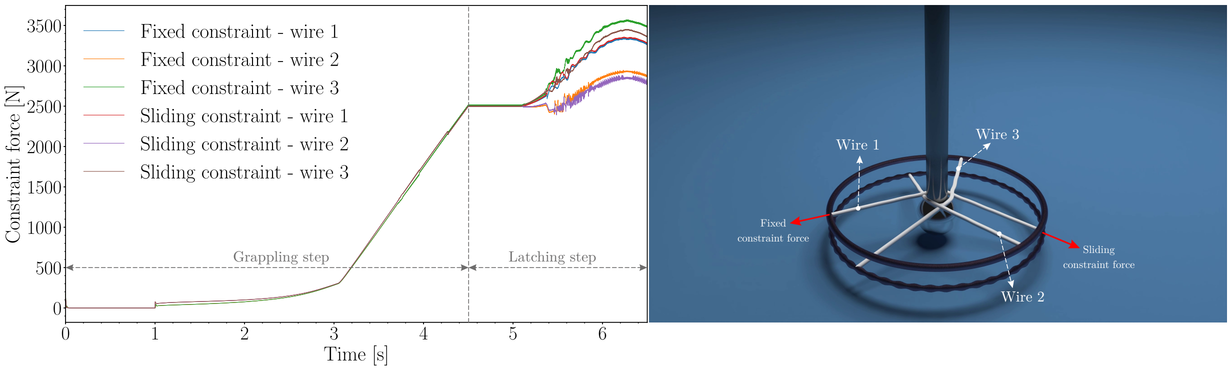

Figure 2: Constraint forces of cables at their fixed and sliding ends. Snapshot of the rendered simulation output at last frame.

Acknowledgments

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References

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