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A cable-driven parallel robots application: modelling and simulation of a dynamic cable model in Dymola

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Abstract. Modeling a cable model in multibody dynamics simulation tool which dynamically varies in length, mass and stiffness is a challenging task. Simulation of cable-driven parallel robots (CDPR) for instance requires a cable model that can dynamically change in length for every desired pose of the platform. Thus, in this paper, a detailed procedure for modeling and simulation of a dynamic cable model in Dymola is proposed. The approach is also applicable for other types of Modelica simulation environments. The cable is modeled using standard mechanical elements like mass, spring, damper and joint. The parameters of the cable model are based on the factsheet of the manufacturer and experimental results. Its dynamic ability is tested by applying it on a complete planar CDPR model in which the parameters are based on a prototype named CABLAR, which is developed in Chair of Mechatronics, University of Duisburg-Essen. The prototype has been developed to demonstrate an application of CDPR as a goods storage and retrieval machine. The performance of the cable model during the simulation is analyzed and discussed.

1. Introduction

Cables in engineering have a variety of usage, in electrical for instance, cables are used for power and signal transmission, for civil engineering, stranded or solid steel cables are used as structural anchors for building and bridge [1]. Meanwhile, in mechanical engineering, cables are mainly used for lifting, hauling and towing in which force is conveyed through tension by pulley and winch mechanism. For electrical and civil engineering applications, cables are basically fixed in length and the only matters are the physical and mechanical properties of the cables such as cross-sectional area, conductivity, specific mass, density, modulus of elasticity, tensile strength, etc. Modeling of cables for these two engineering applications does not need to consider the dynamic change of the cable length. Adversely, in mechanical engineering applications, the variation of cable length, mass and stiffness are necessary especially for dynamic simulation.

Researchers on cables or wire ropes as called in literatures have been carried out for many decades. Most of them have been conducted to serve for specific purposes and needs. For instance, articles from K. Spak et al. [1-3] have analyzed several configurations of stranded helical cables used for spacecraft. The inspected cables served for electrical usage which was modeled and tested in specific length and configuration. In other research by B. Xu et al. [4], an approach to model a steel wire ropes for high energy absorber apparatus is introduced. The work considered three-dimensional contacts between the wire ropes and other objects as well as kink-wave propagation. However, as far as CDPRs is concerned, the approach is not applicable for a dynamic simulation where changing of length is required for every 1 kHz to 2 kHz of the time step. The closest approach is from [5] in which it is implemented in ADAMS software. The cable model is made extensible as well as varies in mass and stiffness. Although the idea and need are alike, the modeling approach and implementation in Dymola or Modelica simulation environments are somehow different. Up to now, there is no string-like cable model that can be dragged in from its library for simulating mechanical systems such as cranes, elevators or alike.

In this paper, an approach is proposed in detail for modeling the cable model using parameters gathered from the factsheet of the cable manufacturer and experimental results. The cable properties are set based on 5mm diameter Dyneema® high-strength, high-modulus polyethylene fiber that is presently being used to actuate the CABLAR prototype. The paper is organized as follows: Section II reviews the theoretical background of cable modeling and relation between discrete system and continuous system modeling. Later on, Section III describes the flow of cable modeling systematically in Dymola. Furthermore, Section IV lists out main parameters of the CABLAR prototype and discusses the simulation results and as well as the cable model performance. Eventually, the achievement and future works of the cable model is summarized in section V.

2. Review of cable mathematical modelling

Theoretically, string-like cables can be mathematically modeled as strings in transverse vibration or rods in axial vibration using either continuous or discrete systems approach. The former approach is described by partial differential equations and the latter is described by ordinary differential equations. Since it is of the same physical system, one should expect both solving approaches would offer similar dynamical behavior if the discrete model were to have a multiple numbers of mass elements in the limit [6].

2.1. Transverse vibration formulation

Considering a boundary value problem in which both ends of the cable are fixed and applying Newton's second law, the equation of motion of the cable in transverse direction can be formulated as follows,

$$T_i \frac{y_{i+1} - y_i}{\Delta x_i} - T_{i-1} \frac{y_i - y_{i-1}}{\Delta x_{i-1}} + F_i = m_i \frac{d^2 y_i}{dt^2} \tag{1}$$

Let a system of discrete masses m_i (i = 1,2,…,n) be connected by massless strings as in figure 1, where the masses m_i are subjected to the transverse forces F_i. To derive the differential equation of motion for typical mass m_i, three adjacent masses m_{i-1}, m_i and m_{i+1} are considered. The tensions in the string segments connecting m_i to m_{i-1} and m_{i+1} are denoted by T_{i-1} and T_i, and the horizontal projections of these segments are Δx_{i-1} and Δx_i, respectively. The displacement $y_i(t)$ ($i=1, 2,..., n$) of the masses m_i are assumed to be small, so that these projections remain essentially unchanged during motion. Moreover, the angle between the string segments and the horizontal are sufficiently small that sine and tangent of the angles are approximately equal to one another. Rearranging the differential equation (1) becomes

$$\frac{T_i}{\Delta x_i} y_{i+1} - \left(\frac{T_i}{\Delta x_i} + \frac{T_{i-1}}{\Delta x_{i-1}} \right) y_i + \frac{T_{i-1}}{\Delta x_{i-1}} y_{i-1} + F_i = m_i \frac{d^2 y_i}{dt^2} \tag{2}$$

Since both ends are fixed, thus the transverse displacement of y_0 and y_{n+1} are set to zero. Further on, set $y_{i+1} - y_i = \Delta y_i$ and $y_i - y_{i-1} = \Delta y_{i-1}$, hence

$$T_i \frac{\Delta y_i}{\Delta x_i} - T_{i-1} \frac{\Delta y_{i-1}}{\Delta x_{i-1}} + F_i = m_i \frac{d^2 y_i}{dt^2}, \qquad i = 1, 2, \ldots, n \tag{3}$$

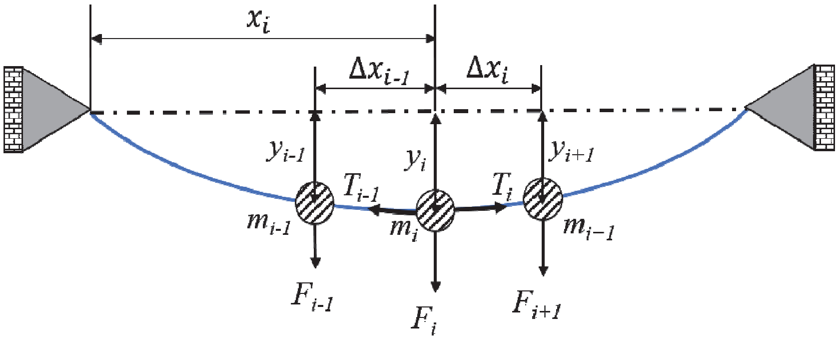

Figure 1. Mass system of a cable in transverse vibration.

Simplifying further equation (3) on it first two terms of the left-hand side, one would write it as

$$\Delta\left(T_i \frac{\Delta y_i}{\Delta x_i}\right) + F_i = m_i \frac{d^2 y_i}{dt^2}, \qquad i = 1, 2, \ldots, n \tag{4}$$

Furthermore, divide equation (4) by Δx, it would be further written as

$$\frac{\Delta}{\Delta x_i}\left(T_i \frac{\Delta y_i}{\Delta x_i}\right) + \frac{F_i}{\Delta x_i} = \frac{m_i}{\Delta x_i} \frac{d^2 y_i}{dt^2}, \qquad i = 1, 2, \ldots, n \tag{5}$$

The second term of equation (5) left-hand side is the distributed transverse force of the cable. Meanwhile, the coefficient of the right-hand side is regarded as its specific mass density at point x. Consider the number of n increase to the limit that $\Delta x \rightarrow 0$, in which one could imagine that the span between masses reduces proportionately with respect to the increase of masses, thus it could be deduced as

$$\frac{\partial}{\partial x}\left[T(x) \frac{\partial y(x,t)}{\partial x}\right] + f(x,t) = \rho(x) \frac{\partial^2 y(x,t)}{\partial t^2}, \quad 0 < x < L \tag{6}$$

In which (6) is considered as the transverse differential equation of the continuous system of the cable that for fixed boundary cases, $y(0,t)$ and $y(L,t)$ is set to zero.

3. Cable modelling in dymola

Based on a brief theoretical derivation in Section 2, the most appropriate way of modeling a cable in Dymola is by using the discrete system. Modeling a string-like cable and having a realistic dynamic behavior of it is obviously challenging in multibody simulation tools. The cable has to be modeled so that it is capable of changing in length, mass, and stiffness with respect to the change of platform pose. On top of that, the cable has to work when it is pulled and not vice versa. All these requirements have to be fulfilled for the cable model to be successfully simulated as actuators of the CDPR model. To make it comprehensible, the modeling procedure is divided into three steps as follows:

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Step 1: Elementary cable model

Considering figure 2, let us start from its basic element which is called a connector. For this instance, they are denoted as `frame_a` and `frame_b`. The names are assigned by default in Dymola for which they represent as input and output connectors of a three-dimensional mechanical model respectively. Besides, they also contain information of the through and across variables of the model. Taking the figure from left to right, it is then followed by three consecutive revolute joints namely `revolute_x`, `revolute_y` and `revolute_z` which are used to allow free motion to the cable in three rotational axes, i.e. roll, pitch and yaw.

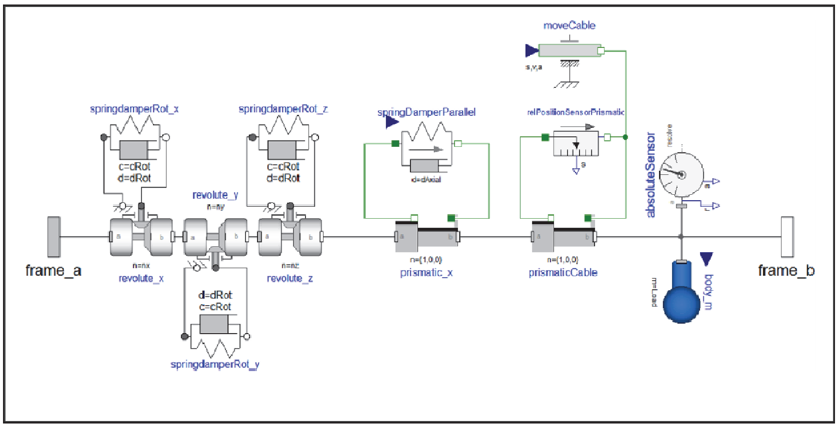

Figure 2. Elementary model of the cable.

Together with every single revolute joint is a one-dimensional rotational spring-damper so-called `springdamperRot_x`, `springdamperRot_y` and `springdamperRot_z` that are used to limit the rotational motion of every single revolute joint. Furthermore, two prismatic joints are set in the elementary cable model. The first prismatic joint is called `prismatic_x` as the horizontal direction between connectors is considered as the x-axis. This specific prismatic joint is assigned to provide elastic behavior within the cable's elementary element. It is attached in parallel with a modified one-dimensional translational spring damper named as `springDamperParallel`. The blue triangle next to it is a real input connector used to link the model to the external input from the upper-class model. The second prismatic joint is called `prismaticCable`. This prismatic joint serves as a length-changer for the elementary cable model. Connected parallel to it is two default models that are called `relPositionSensorPrismatic` and `moveCable` in which they serve as a sensor to measure the relative length with respect to its initial length, l_0 and actuator to the prismatic joint. Furthermore, in order to link the elementary cable with gravitational influences, a mass element, i.e. `body_m` is considered. The chosen mass element or rigid body consists of mass and inertia tensor as input parameters. To make it rational, the mass and inertia tensor ought to vary with regard to the change of cable length and this should happen simultaneously within the cable. Therefore, a similar procedure applied to `springDamperParallel` element in `prismatic_x` is also carried out on the mass element, a real input is attached to it as to allow variable mass inputs to be transferred from the upper-class model.

Step 2: Intermediate cable element

Now, Step 2 explicitly shows the second layer of the cable model named as an intermediary or middle layer. It is used to link the upper cable model to its elementary model.

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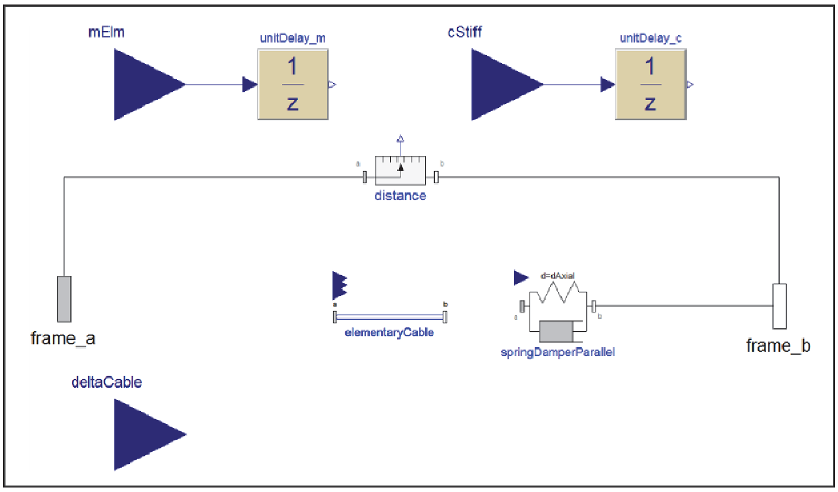

Figure 3. Intermediate model of the cable.

Considering figure 3 from left to right, the intermediate model starts with `frame_a` as the input connector. Then, it is followed by `elementaryCable` which is the outlook of the lower class model of Step 1. There are three real inputs attached on top of its input frame that allow it to connect with the upper-class model. They are used to inherit variable inputs of cable length, mass, and stiffness for the elementary cable model. Next to it is a three-dimensional `springDamperParallel` which is used to provide elasticity behavior on the overall cable model. There is also a real input attached to it for inheriting the variable stiffness. To make it understandable and easy to model, the stiffness of the cable is formulated as

$$k_{c_{Total}} = \frac{EA}{l_0 + \Delta l} \tag{7}$$

in which E is Young's modulus of the cable, A is the cross-section area of the cable and Δl is the change of cable length. Therein, the stiffness of each cable element is derived further as

$$k_{c_{element}} = \frac{k_{c_{Total}}}{nElm + 1} \tag{8}$$

where $nElm$ is a pre-defined number of cable element. The addition of one in the denominator of equation (8) signifies the additional spring stiffness for the three-dimensional parallel spring damper element. Furthermore, as to relate to the change of cable length, the mass of cable is formulated as

$$m_{c_{Total}} = \rho V = \rho A l = \rho A(l_0 + \Delta l) \tag{9}$$

where V is the cable volume, which can be calculated from its diameter, d and length, l whereas its density, ρ is taken from the manufacturer factsheet. Hence, for single element, the mass is further deduced as

$$m_{c_{element}} = \frac{m_{c_{Total}}}{nElm} \tag{10}$$

In the case of cable density is unknown, instead of using equation (9), one could also use the specific mass of the cable or cable mass per unit length, m_{spec} as shown in equation (11).

$$m_{c_{element}} = \frac{m_{spec} l}{nElm} = \frac{m_{spec}(l_0 + \Delta l)}{nElm} \tag{11}$$

Considering figure 3 further, there are three real inputs used to connect the current cable model to its upper class named as `deltaCable`, `mElm` and `cStiff`. For initialization and discretization of the cable model, `unitDelay_m` and `unitDelay_c` are used to predefine the initial cable mass and stiffness. The initial of both variables are defined as in equation (7) and equation (9) by excluding the change of cable length, Δl. Finally, the intermediate model is wrapped up by an output connector `frame_b`.

Step 3: Top cable element

The top layer of the cable model consists of a user interface as indicated in figure 4. Here, all the important parameters of the cable are predefined. As could be seen in the figure, the cable parameters are separated into three parts. The first part is a general part in which user has to define the number of cable element, *nElm* and initial length of the cable, l_0.

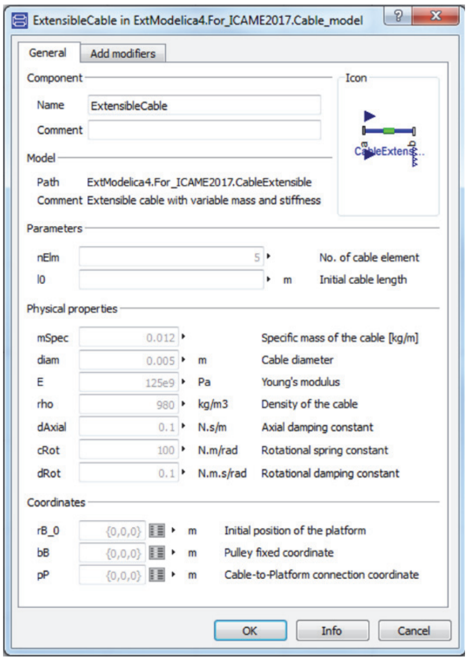

Figure 4. Parameter dialog of the cable model.

Besides, ones could choose any finite number of cable elements that suit their need. Note that, by having more elements in line, the cable model would react closer to real cable and possess sagging and oscillation effects. This fact has been explained in Section II, where discrete and continuous systems have been correlated. However, too many elements would trade off the computing time accordingly. Later comes the initial length, `l0` of the cable in which for CDPR case, the length has to be pre-calculated by inverse kinematics. Then, it is followed by a list of common physical properties of the cable that have been gathered from the factsheet and experiment such as its specific mass per unit length, `mSpec`, diameter, `diam`, Young's modulus, `E`, density, `rho`, and as well as the damping properties. Finally, yet importantly, it is followed by main reference coordinates of CDPR such as the initial platform position, `rB_0`, fixed coordinate of the pulley, `bB`, and the cable-to-platform connection point, `pP`. For a clearer view, placement of the major coordinates is shown in figure 5. The first two coordinates have to be set with reference to its inertial frame, *O* whereas the third coordinate has to be set with respect to the local coordinate of the platform, *P*. The green, red and blue arrows respectively represent the direction of the coordinate vectors.

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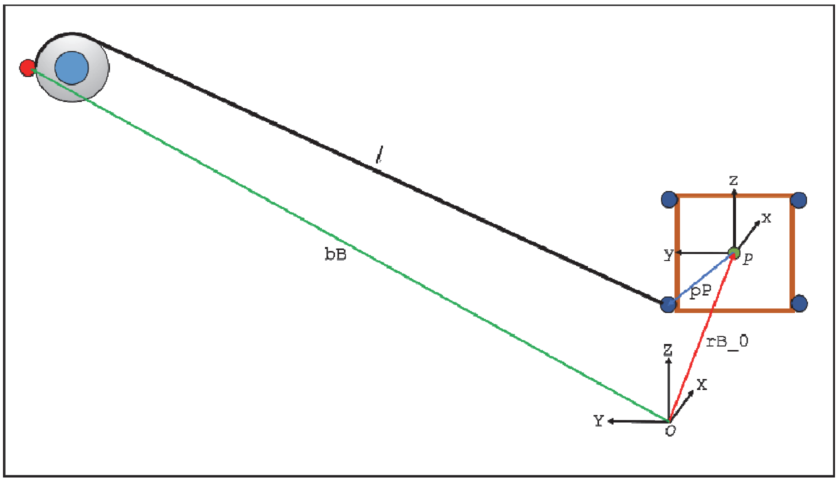

Figure 5. Layout of CDPR major coordinates.

To make it understandable, the flow of input and output variables of the cable model is summarized in figure 6. Respectively, note that the flow of modeling process is opposite to the simulation flow.

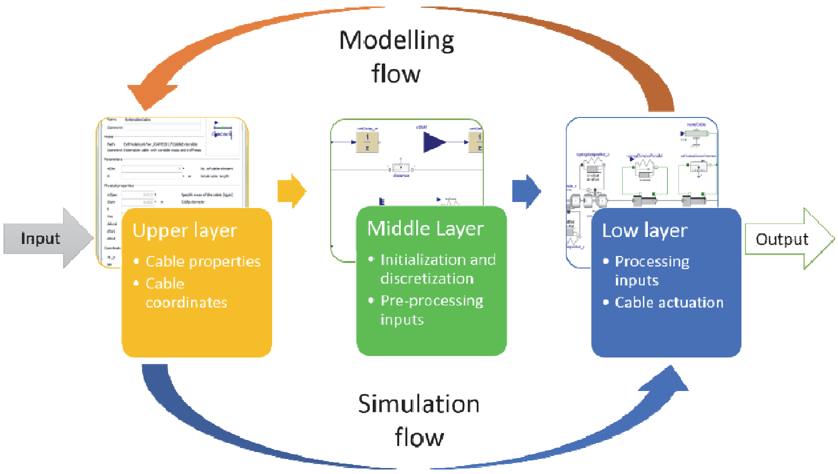

Figure 6. Process flow of cable modeling.

4. Results and discussion

4.1. Simulation setup

Simulation of the cable model is carried out on a complete CDPR model in which the parameters are based on the CABLAR prototype developed in Chair of Mechatronics, Universität Duisburg-Essen. The prototype is a planar eight-cable CDPR, which is meant for goods storage and retrieval operation. The main coordinates of the prototype are tabulated as follows

Table 1. Pulley fixed coordinates

Pulley fixed coordinates, bB_i	x(m)	y(m)	z(m)
bB_1	0.4000	-5.0791	0.5335
bB_2	0.4000	-5.1289	0.5269
bB_3	0.4000	-5.0992	4.7472
bB_4	0.4000	-5.1114	4.7549
bB_5	0.4000	5.0873	0.5142
bB_6	0.4000	5.1144	0.5314
bB_7	0.4000	5.1136	4.7678
bB_8	0.4000	5.1240	4.7688

Table 2. Cable-to-platform connection points

Cable-to-platform points, pP_i	x(m)	y(m)	z(m)
pP_1	0.0420	-0.4530	0.2350
pP_2	-0.0420	-0.4530	0.2350
pP_3	0.1375	-0.4530	-0.2350
pP_4	-0.1375	-0.4530	-0.2350
pP_5	0.0420	0.4530	0.2350
pP_6	-0.0420	0.4530	0.2350
pP_7	0.1375	0.4530	-0.2350
pP_8	-0.1375	0.4530	-0.2350

Table 2 and 3 are the input parameters for all eight cables of the CDPR model that set the initial direction vector of the cables in terms of position and orientation. Note that, the pP_i is the coordinates of the cable-to-platform connection points with reference to the local coordinate system of the platform. The following tabulated figures in table 3 are a list of major properties of Dyneema cable applied in the cable model.

Table 3. Major properties of the cable model

Cable Properties	Figures
Modulus of elasticity, E	109 - 132 GPa
Density, ρ	970 - 980 kg/m^3
Area of cross-section, A	19.635x10^{-6} m^2
Damping constant, c	10 N.s/m
Diameter, d	0.005 m

Table 4. Trajectory coordinates of the platform

Trajectory coordinates, P_i	x(m)	y(m)	z(m)
P_1	0.0000	-2.5000	1.3600
P_2	0.0000	0.8050	2.0000
P_3	0.0000	2.9800	1.3900
P_4	0.0000	-2.0000	2.0000
P_5	0.0000	0.8050	2.0000
P_6	0.0000	0.2030	1.4000
P_7	0.0000	-2.0000	2.0000
P_8	0.0000	1.1650	2.0000
P_9	0.0000	0.2300	1.3800
P_{10}	0.0000	-2.2000	1.7000
P_{11}	0.0000	1.1650	2.0050
P_{12}	0.0000	2.0000	1.4100
P_{13}	0.0000	0.0000	0.7650

For simplification, the damping properties of the cable have been considered as constant throughout the simulation even though based on the experiment, the axial damping constant is varied below the given figure. Therefore, the given damping constant has been considered as the maximum damping constant for simulating the CABLAR CDPR model. Furthermore, it is also discovered that the damping properties changed dynamically with respect to cable tension and length. Physical experiment on the cable has shown that an increase of cable tension proportionally reduces the damping constant whereas an increase of cable length correspondingly increases the damping constant. To test the cable model to it limit, a set of trajectory coordinates as listed in table 4 are used for the simulation. The complete cable robot model is simulated for 70 seconds on a system with specification given as in table 5.

Table 5. System Specification

Specification details	
Windows edition:	Windows 7 Enterprise
Processor:	Intel® Core™ 2 Quad Q6600 @ 2.4 GHz
Installed memory (RAM):	4.00 GB
System type:	64 Bit Operating System

4.2. Validation of cable model

For validation, static analysis is conducted on the cable by a pure bending test. The sagging of the cable model with regard to a variation of cable length is simulated and compared with the results of cable sagging from the experiment. The experiment is conducted such that the cable is let to fall freely due to gravity at minimum cable tension of 6N. The same setup is model in Dymola. The setup of the experiment is as shown in figure 5. The results of the experiment and simulation are tabulated as in table 6. The vertical displacement of the mid-mass element of the cable model is cable model is compared with the experimental results of a free fall sagging test.

Table 6. System specification

Cable length (m)	Sagging (mm)		Absolute error (mm)
	Experiment	Simulation	
0.90	1.677	1.673	0.004
1.15	2.889	2.879	0.010
1.40	4.470	4.469	0.001
1.65	6.436	6.431	0.005
1.90	8.800	8.753	0.047
2.15	11.576	11.553	0.023
2.40	14.775	14.657	0.118
2.65	18.407	18.401	0.006
3.00	24.237	24.134	0.103

4.3. Simulation results

Based on the trajectory coordinates listed in table 4, the desired and simulation trajectory of the CDPR is sub-plotted as depicted in figure 7. The axes are plotted separately so that the behavior of the platform with respect to the desired trajectory for every single Cartesian coordinate can be clearly visualized. Note that, since it is a planar type CDPR, the movements are obviously significant on y and z-axes. As can be observed, the trajectory of the platform for y and z-axes are successfully controlled except for x-axis.

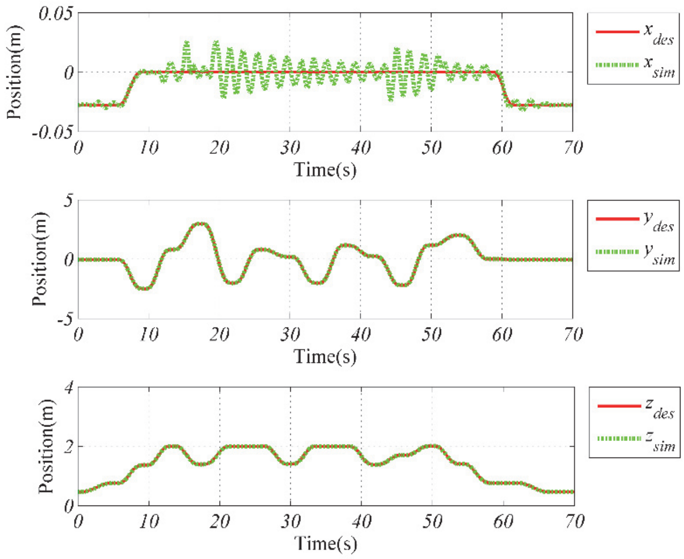

Figure 7. Comparison between the desired and simulation position of the platform.

Through the generated animation, it is clearly viewed that the platform is wobbling in x-axis for every coordinate-to-coordinate transition. The wobbling range is within 2 centimeters and similar behavior is observed on the prototype. Up to now, it can only be described qualitatively as there is no specific onboard sensor available in the market to measure the real-time pose of the platform. Furthermore, this kind of behavior on the platform happened when the stiffness and mass of the cables are made to vary with respect to the change of their length.

On the other hand, the orientation of the platform consists of its roll, pitch and yaw are shown in figure 8. The range of orientation overshoots due to coordinate-to-coordinate transition within 2 degrees.

To show the achievable variation of cable length throughout the simulation, instead of showing all the eight cables variation, which may cause cumbersome, four selected cables have been chosen and plotted in figure 9. Taking cable 1 (c1) in solid red line, for example, the length and stiffness are inversed proportional to each other. As the cable length grows longer, the stiffness of cable drops correspondingly. This successfully shows the relation between cable length and its stiffness as in equation (7). Meanwhile, the mass of the cable is proportionally correlated with the change of cable length. This correlation has been described in equation (9). This kind of correlation is important for multibody dynamic analysis as it displays a true behavior of the developed model specifically for a nonlinear element such as string-like cable.

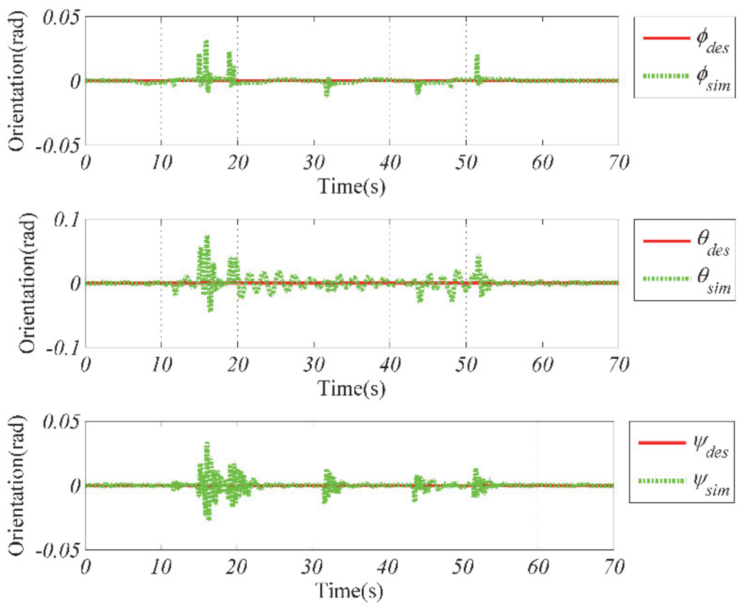

Figure 8. Comparison between the desired and simulation orientation of the platform.

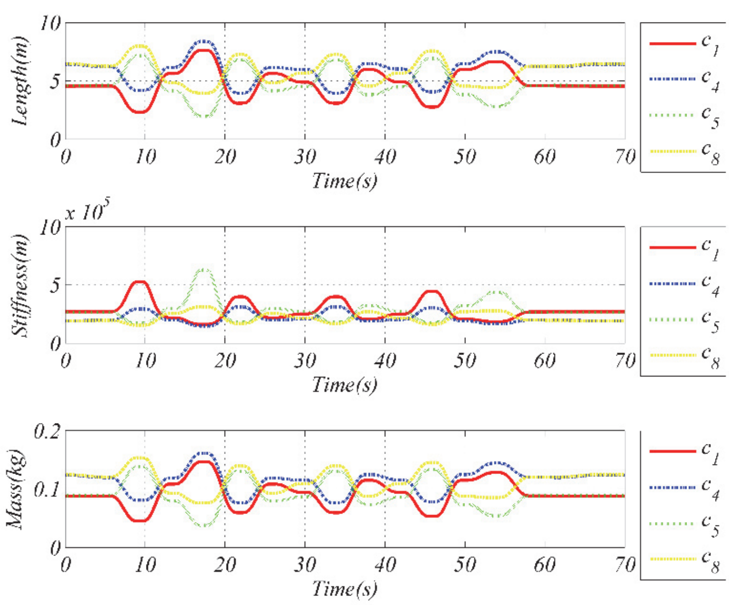

Figure 9. Variation of cable length, stiffness, and mass with respect to the trajectory planning of the platform

5. Conclusion and future works

This paper introduced in detail the procedure of developing a dynamic cable model, which is useful for performing a dynamic analysis of CDPR. The cable model was dynamically varied in stiffness and mass with respect to the change of its length. Despite complex trajectory, the CDPR platform was well tracked and controlled, which somehow due to correct approach of modeling the cable. Qualitatively, the behavior of the platform based on coordinate-to-coordinate transition has shown the close behavior of the CABLAR prototype. Besides that, the cable model could be used to simulate different type of string-like cable applications such as crane and elevator systems. Furthermore, the cable modeling approach could be applied to other Modelica simulation environments such as OpenModelica, MapleSim, SimulationX and many more. For future works, the subjected cable will be examined further using an improved experimental setup for discovering its true dynamic properties such as stiffness and damping as they showed very strong correlation. From the experimental data, a function that relates its dynamic properties with the change of length and tension will be modeled and deems to tackle hysteresis problem of the cable as well as give more realistic behavior to overall CDPR and string-like cable applications.

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