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Cable-Driven Parallel Robot simulation using Gazebo and ROS

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Abstract. In this paper, we present a simulator that has been developed using Gazebo and ROS to study cable-driven parallel robots. Real-time dynamic simulation of such robots is an efficient approach to develop new control laws that may integrate various sensors. The limitations of Gazebo are dealt with, as we model the cables under tension as massless $U - \underline{P} - S$ links with the prismatic joint actuated. We illustrate the proposed simulator with a dynamic controller, detailing the tension distribution and performing various trajectories.

1 Introduction

The study of Cable-Driven Parallel Robots (CDPR) has been one of the active fields of robotics research for several decades ([1]). CDPRs are an extension of the idea of parallel robots where the rigid links of the parallel robot are replaced with cables under tension to form a cable-driven parallel robot. They usually consist in a number of cables attached to a fixed base, with the other end attached to a common end-effector. Tensions are applied to modify the length of the cable and thus obtain a motion of the end-effector. CDPRs advantages are negligible inertia, low weight, fewer mechanical components and a high payload-to-weight ratio.

The simulation of CDPR presents a difficulty related to the representation of cables in software, modeling the sagging effects induced by cables of non-negligible mass and extensibility of cables depending on the operating condition or cable material used. The approach from [2] simulates a cable in ADAMS software by a discretization of the cable into rigid elements that are connected by bushing forces. The actuated prismatic joint between cable elements allow the translational motion of the cable on axis lying along the cable. Another approach using XDE ([3]) and Matlab/Simulink to create a simulation and control of a CDPR is seen in [4].

We have chosen to assess the Gazebo simulator [5]. Gazebo is an open-source dynamic simulator based on ODE (Open Dynamic Engine) or Bullet physics. It is considered as a reference in robot simulation: DARPA challenge in [6], underwater manipulators in [7] or aerial robots in [8]. Besides the dynamic part, it can simulate various sensors through a plugin interface: IMU, cameras, laser scanners. This makes it a strong platform to test and experiment complex control laws not limited to a home-made dynamic simulation. Gazebo is also compatible with ROS, leading to a modular and organized architecture for robot simulation, including communication between different components.

This paper aims to present the methodology to simulate a CDPR in Gazebo with some results on trajectory tracking.

2 CDPR modeling

2.1 Kinematics of cable robots

A CDPR can be seen as a moving platform (considered as the end-effector) linked to a fixed base through several cables, assumed to be always on tension. For cable i, point A_i with coordinates $\mathbf{a}_i$ (written in the base frame) defines the attach point on the base while point B_i with coordinates $\mathbf{b}_i$ (written in the end-effector frame) defines the attach point on the end effector. The homogeneous transformation matrix from the end-effector to the global frame is given as:

$$\mathbf{T} = \begin{bmatrix} \mathbf{R} & \mathbf{t} \\ \mathbf{0}_{1\times 3} & 1 \end{bmatrix} \tag{1}$$

where $\mathbf{R}$ defines the rotation matrix and $\mathbf{t}$ the center of mass position vector of the end-effector.

2.2 Inverse and Differential Kinematics

From a given pose $(\mathbf{t}, \mathbf{R})$ of the end-effector, any cable i can be written with a vector $\mathbf{l}_i$:

$$\mathbf{l}_i = \mathbf{a}_i - \mathbf{t} - \mathbf{R}\mathbf{b}_i \tag{2}$$

The Jacobian matrix $\mathbf{J}$ gives the relationship between the time-variation of the cable lengths $\dot{\mathbf{l}}$ and the twist of the moving platform $\mathbf{v}$:

$$\dot{\mathbf{l}} = \mathbf{J}\mathbf{v} \tag{3}$$

where:

$$\mathbf{J}_{mxn} = \begin{bmatrix} -\mathbf{d}_1^T & (\mathbf{d}_1 \times \mathbf{R}\mathbf{b}_i)^T \\ -\mathbf{d}_2^T & (\mathbf{d}_2 \times \mathbf{R}\mathbf{b}_2)^T \\ \vdots & \vdots \\ -\mathbf{d}_n^T & (\mathbf{d}_n \times \mathbf{R}\mathbf{b}_n) \end{bmatrix} \tag{4}$$

where $\mathbf{l} = (\|\mathbf{l}_1\|, \|\mathbf{l}_2\|, ..., \|\mathbf{l}_n\|)$ is the cable length vector and $\mathbf{d}_i = \frac{\mathbf{l}_i}{\|\mathbf{l}_i\|}$ is the unit vector along cable i.

2.3 CDPR dynamics

We will consider the dynamic modeling of a cable robot whose cables are assumed to have negligible mass and are not elastic ([9]). With this assumption, the dynamics is reduced to only that of the end effector while ignoring the dynamics of the actuator or pulley:

$$\mathbf{M}\ddot{\mathbf{x}} + \mathbf{C}\dot{\mathbf{x}} - \mathbf{w}_g - \mathbf{w}_e = \mathbf{W}\mathbf{f} \tag{5}$$

where $\mathbf{M}$ is the spatial inertia matrix of the moving platform, $\mathbf{C}$ gathers the centrifugal and Coriolis wrenches, $\mathbf{w}_g$ is the gravity wrench and $\mathbf{w}_e$ gathers the external wrenches that are not coming from the cable tensions. The cable tensions $\mathbf{f}$ are linked to the resulting wrench by the wrench matrix $\mathbf{W} = \mathbf{J}^T$. From (5), the static equilibrium is reached when $\mathbf{W}\mathbf{f} + \mathbf{w}_g + \mathbf{w}_e = 0$.
We now detail CDPR modeling and assumption for the Gazebo simulation.

3 CDPR in Gazebo simulator

Robot models and properties are described in Gazebo using the simulation description format (SDF) which is an XML file that describes objects and environments for robot simulators, visualization, and control. The resulting simulated robot can be seen in Figure 1. In this section we detail the assumptions that are done for the various components of the robot. We then expose the SDF file generation, before considering the inputs, outputs and potential control laws that can be used with the simulator.

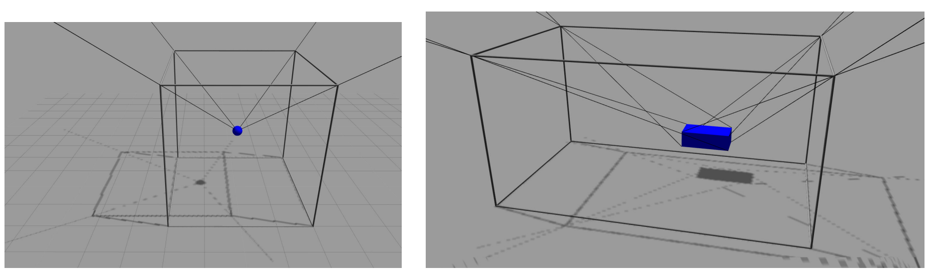

Fig. 1: Simulated Cable Robot with point mass end effector (left) and 8-cables CAROCA ([10]) robot (right)

3.1 General modeling

Base frame: The fixed base is modeled as a single parallelpiped cuboid, used only for visual rendering. The attach points A_i can be defined anywhere in the base frame, they are typically on the vertices of the cuboid. For stability, the fixed based is given a nearly infinite mass, inducing a static behavior during the dynamic simulation.

Moving platform: The moving platform can be given an arbitrary mass and inertia matrix. In figure 1, we show two examples of the moving platform: a sphere-shaped platform with 4 cables attached at the same position (left) and a box-shaped platform with 8 cables attached on its vertexes (right). The visual can be any geometric primitive, or a 3D mesh if it is available.

Cables: Cables are modeled using the massless inextensible model. We thus approximate the cables as rigid cylinders of negligible mass and inertia, as it is common in dynamic simulation of rigid objects. Gazebo cannot render bodies of variable dimension, hence the lengths of the cables are defined to their maximum value. In practice, a portion of the cable is thus going out of the fixed frame as it can be seen in figure 1. Cables being massless, this has no impact on the simulation.

Joints In practice, the modeled CDPR is actually a parallel robot with universal-prismatic-spherical (U-P-S) architecture with the prismatic joint actuated ([11]). This requires virtual links with a Universal joint to the platform and a Prismatic one to the cable. These links are defined with negligible masses. These links may also be used to render a pulley offset if needed, but it is not taken into account in the current form of the simulation. All joints can be defined with damping, by default the Universal and Spherical joints are passive, frictionless joints. The built-in difference with a classical parallel robot is that a module makes it impossible to apply any negative effort on the Prismatic joints. This makes it mandatory to have a controller that outputs positive tensions, hence simulating a CDPR.

3.2 SDF file generation

An SDF file contains all properties of a given robot: mass, inertia, pose, link visual and collision, damping and limits in position, velocity and effort for the joints. As this file is very tedious to write by hand for CDPR, an automated generation is done from a simple GUI allowing to define:

- The dimensions of the base frame, that is assumed to be a parallelpiped cuboid of nearly infinite mass
- The dimensions, visual, mass and inertia of the moving platform
- The coordinates of the exit points A_i in the base frame and the anchor points B_i in the platform frame
- The passive and active joint properties
- The home position of the platform

3.3 Simulator I/O and control

The only inputs or the simulation are the cable tensions, seen as prismatic joint efforts. As previously stated, any negative effort will be ignored as it is not possible to apply negative tensions in CDPR. Being a ROS-compatible simulator, Gazebo can publish all information about links and joints (poses, efforts, velocities, etc.). They can be captured by any Python or C++ software as inputs for a control law or to get the ground truth. Other sensors may be introduced (cameras, IMU...) to experiment on more complex control or behavior.

CDPR controllers may output either desired cable lengths or desired cable tensions. While desired tensions can be directly interfaced with the simulator, a position-based controller (i.e. using inverse kinematics) will need to be complemented with a low-level PID that computes a cable tension from the length error, as in a real motor drive.

We now expose some simulation results based on trajectory tracking using a tension controller.

4 Simulation demonstration

In this section, a trajectory tracking is demonstrated for the CAROCA ([10]) robot. We first briefly expose the overall controller before showing the simulation results.

4.1 Trajectory tracking

A classical framework is used to perform trajectory tracking: first the trajectory is defined in terms of desired pose, velocity and acceleration. A tracking controller then computes the desired wrench to be applied to the platform. Finally, a Tension Distribution Algorithm maps the desired wrench to the cable tensions.

The trajectory generation is used to pass through a number of waypoints, using 5th order polynomial. This is a classical approach for CDPR and lead to known time-based functions for desired pose $\mathbf{x}_d(t)$, velocity $\dot{\mathbf{x}}_d(t)$ and acceleration $\ddot{\mathbf{x}}_d(t)$.

Feedback linearisation of the dynamic model ([12]) is then used to to stabilize the system to desired trajectory. The acceleration to be performed by the platform is defined as:

$$\ddot{\mathbf{x}} = \ddot{\mathbf{x}}_d + \mathbf{K_p}(\mathbf{x_d} - \mathbf{x}) + \mathbf{K_d}(\dot{\mathbf{x}}_\mathbf{d} - \dot{\mathbf{x}}) \tag{6}$$

where $\mathbf{K_p}$ and $\mathbf{K_d}$ are control gains. From the static equilibrium described in Section 2.3, this acceleration is mapped to the desired cable wrench $\mathbf{w}$:

$$\mathbf{w} = -(\mathbf{M}(\ddot{\mathbf{x}}_d + \mathbf{K_p}(\mathbf{x_d} - \mathbf{x}) + \mathbf{K_d}(\dot{\mathbf{x}}_\mathbf{d} - \dot{\mathbf{x}})) + \mathbf{w}_g) \tag{7}$$

Finally, this desired wrench is transformed into cable tensions through the 2-norm optimal solution ([13]). This approach finds the minimal norm tensions $\mathbf{f}$ that satisfy the wrench constraint $\mathbf{Wf} = \mathbf{w}$ and that are inside the acceptable tensions range $[f^{\min}, f^{\max}]$

$$\begin{aligned} \mathbf{f} = \arg\min \|\mathbf{f}\|^2 & \\ \text{s.t. } \mathbf{Wf} = \mathbf{w} & \\ \text{s.t. } \forall i, 0 < f^{\min} \leq f_i \leq f^{\max} & \end{aligned} \tag{8}$$

This can be solved in real time through a quadratic programming (QP) solver. We now expose the simulation results.

4.2 CAROCA robot carrying 1 kg and 15 kg mass to perform a desired 5th order polynomial trajectory

We simulate a CAROCA robot ([10]) carrying different masses of 1 kg and 15 kg. The robot has a simple point-to-point trajectory to perform within its workspace and we do not consider it's orientation. The parameters used are $K_p = K_d = 1500$, $t_{min} = 1N$, $t_{max} = 6500N$ The tensions obtained from the

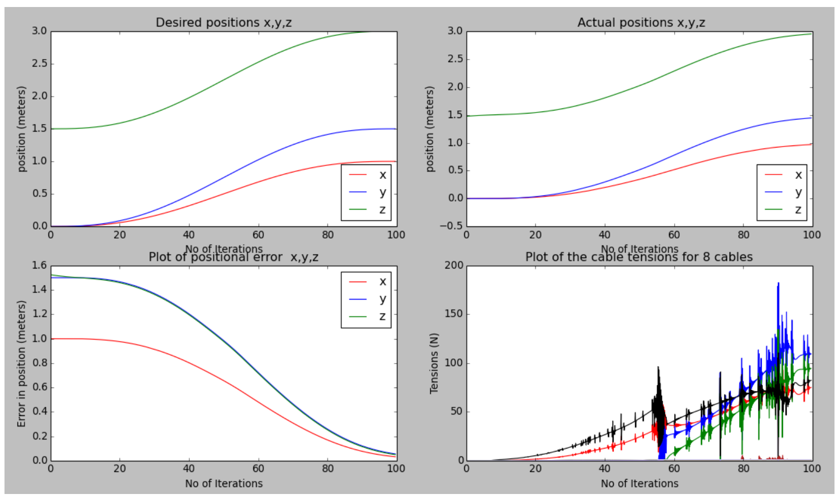

Fig. 2: CAROCA robot with 1 kg mass at the end-effector. Desired (upper left) and actual positions (upper right), position errors (lower left) and cable tensions (lower right).Output tensions are not continuous due to numerical errors.

optimization and applied to the robot and the position error can be seen in figure 2 for the 1kg mass and figue 3 for the 15kg mass. In both cases we see that the position error tends to zero, the tension positivity condition is respected and the tensions applied to the robot stays within the desired tension limits. The spikes seen in the tension values result from the solutions to the numerical optimization which are not continuos in time but are valid under positivity conditions and bound conditions . As different masses are simulated, the control and simulation adapts and we see higher tensions are applied when carrying 15 kg.

4.3 CAROCA robot with 15 kg mass performing an S-curve trajectory

In this section, we show how this simulator can be used to perform pick-and-place experiments by performing an S-curve trajectory as seen in figure 4. Similarly to

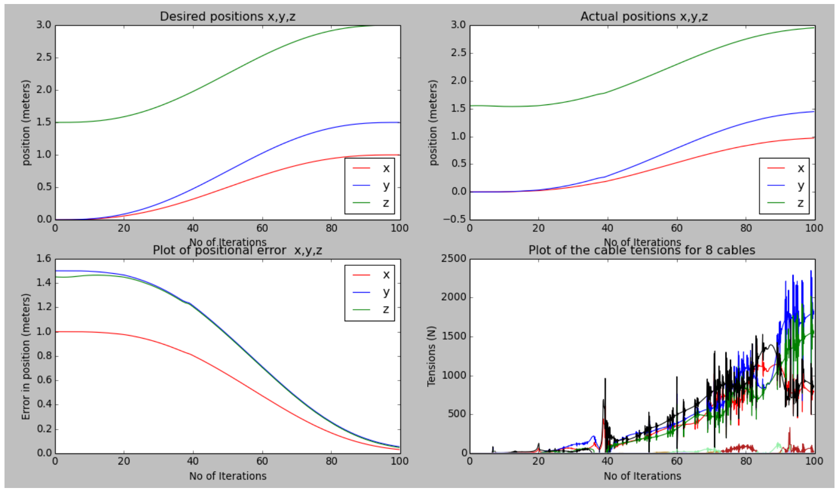

Fig. 3: CAROCA robot with 15 kg mass at the end-effector. Desired (upper left) and actual positions (upper right), position errors (lower left) and cable tensions (lower right).Output tensions are not continuous due to numerical errors.

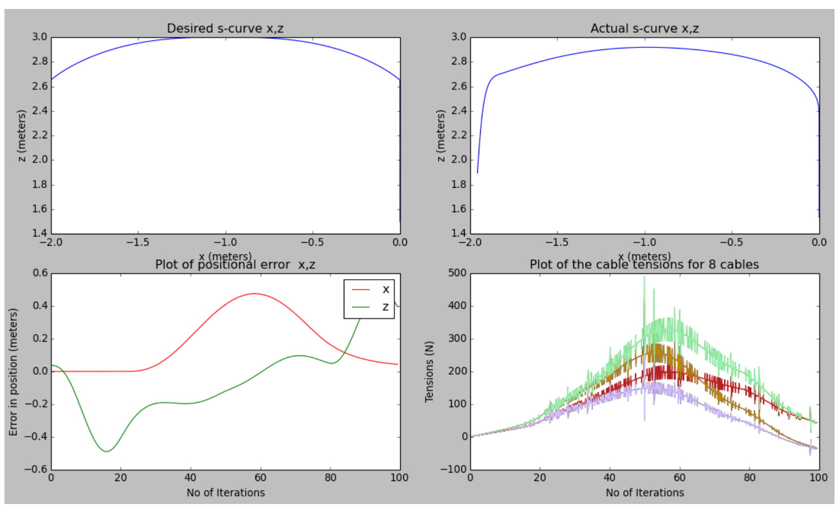

Fig. 4: CAROCA robot performing an S-curve trajectory

the previous experiment, the simulator is able to take into account the computed tensions and to render a realistic trajectory.

4.4 Conclusion and Future work

From this work, we have shown how Gazebo and ROS can be used to simulate and perform simple dynamic control of a cable-driven parallel robot. This methodology approximates the cables to rigid links, which do not hold under all scenarios. An advantage of our approach is that it is real-time enabling fast simulation. The use of Gazebo makes it very modular and capable of adding other sensors, obstacles or even robots to simulate different complex scenarios. In the future, the current rigid cables will be replaced by an open plugin allowing customized cable models.

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