Development of a Dynamic Simulator for Cable-driven Parallel Robots

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THESIS BIBLIOGRAPHY STUDY FOR
MASTER AUTOMATIQUE, ROBOTIQUE ET INFORMATIQUE APPLIQUÉ

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January 18, 2016

Abstract

This report studies the current state-of the art of simulators for cable driven parallel robots. In particular, we are interested in the current developments of a dynamic simulators for cable-driven parallel robots. We make a recall on cable driven parallel robots, their static and dynamic properties. We also make a further study of robot simulation softwares that are available today, in particular, Gazebo and how it can be integrated with ROS to achieve our objectives of developing a simulator for cable-driven parallel robots that can also work with vision and other sensors. Then we make a comparison of the advantages we hope to gain from developing a simulator in gazebo to other existing software

Contents

List of Figures

Abbreviations

ROS - Robot Operating System

CDPM - Cable-driven Parallel Manipulator

CDPR - Cable-driven Parallel Robot

MATLAB - Matrix Laboratory

EU -FP7 - European Union Seventh Framework Program

PID - Proportional-Derivative-Integral Controller

3D - Three Dimensional Space

2D - Two Dimensional Space

FC - Force Closure Workspace

WFW - Wrench Feasible Workspace

WCW - Wrench Closure Workspace

IFCOW - Interference Free Constant Orientation Workspace

DARPA - Defence Advanced Research Projects Agency

OSRF - Open Source Robotics Foundation

ODE - Open Dynamics Engine

GUI - Graphical User Interface

SDF - Simulation Description Format

XML - Extensible Markup Language

URDF - Universal Robot Description Format

GPS - Global Positioning System

LTS - Long Time Support

Chapter 1

Introduction

The study of parallel robots has been one of the active fields of robotics research for several decade. [10].Parallel Robots present several advantages such as high accuracy and high accelerations and a large payload-to-weight. They usually consist of a number of links fixed to a base and with the other end attached to a common end effector.

Cable driven parallel robots are an extension of the idea of parallel robots by a combination of the principles of parallel robots with the properties of cables. In other words, the rigid links of the parallel robot has been replaced with a cable under tension to form a cable driven parallel robot

CDPMs come with the advantage of having negligible inertia, lighter and fewer mechanical components to give a lighter assembly, larger workspace than conventional parallel robots.

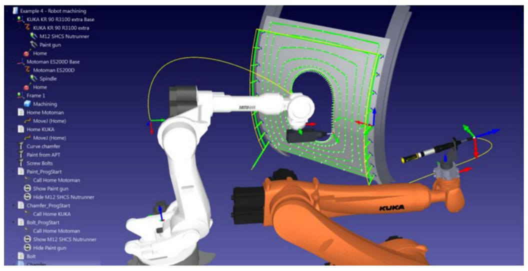
An important stage in the process design of cable driven parallel robots is the simulation phase. Simulators allow us to quickly test a new idea and see how this implementation fits our design.

Design of robots make use of simulators test how the robot will operate under certain conditions before we begin the expensive journey of building an actual robot. Also it can be quite dangerous for robots if the designer decides to deploy a new algorithm which has not been tested in simulation.The robot can be damaged if something goes wrong or if some parameters had not been taken into account.

Having a good visual representation of the robot's workspace is also quite interesting to show the capabilities of a robot to an audience who could be interested in investing in such a project or to an audience who want to learn about these robots. Simulating interactions between this robot and the environment or between this robot and objects also help us to study these robots and really test them to the limits.

Our focus on this study is to look at existing work that has been done to implement simulators for cable driven parallel robots and how we can use Gazebo to implement a simulator for a Cable driven parallel robot.

Gazebo presents powerful tools that we can use to achieve this. But currently, there is no existing cable driven parallel robot simulator that has been implemented in Gazebo at the time of this publication to the best of our knowledge. Thus this gap presents an opportunity for us to define a simulator that can be used in the teaching and research of cable driven parallel robots by the community.


(a) Industrial Machine Simulation using Robo DK software

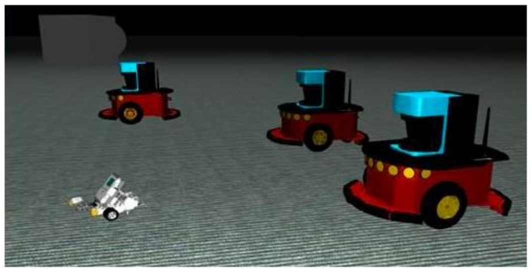

(b) Mobile Robots Simulated in Microsoft Robot Development Studio

Figure 1.1: Examples of Robot Simulation in Software [1]

There exists some implementation of CDPMs simulators [11] [2] which are developed using MATLAB/Simulink.

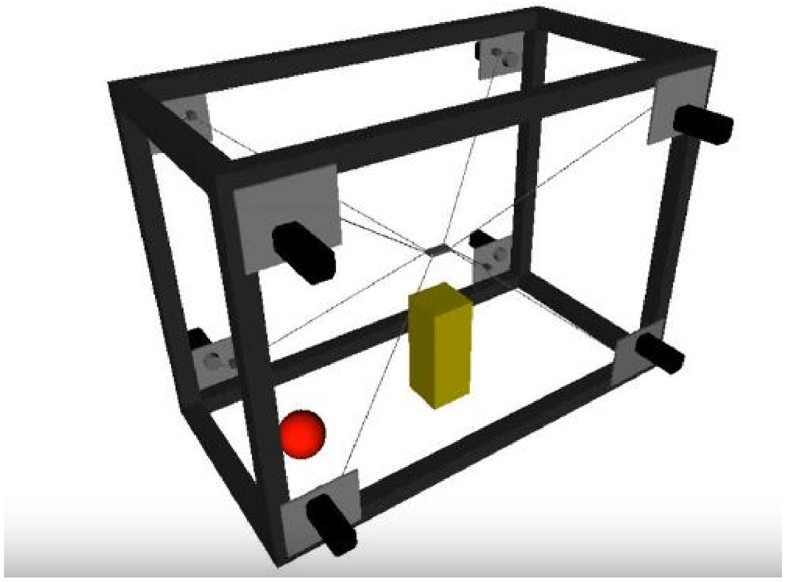


Figure 1.2: Cable Driven Parallel Robot 3D Simulator developed by means of MATLAB/SIMULINK [2]

1.1 Literature Review

The earliest built CDPM was NIST ROBOCRANE [12] Another early application is seen in SKYCAM [13], where cables are used to move a camera over a football field. The advantage here is the large workspace covered by the CDPM and that there is no interference of the view of the spectators by the cable due to their small size.

CDPMs have also been employed in construction[14] and medical rehabilitation [15]. A system for teleoperation [16] has been proposed based on cable driven parallel robots and other for cable system for space-craft application is seen in [17].

Dynamic Workspace has been defined by the authors in [18] while Force Closure Workspace (IFCOW) has been defined by [19]. The set of wrenches that the CDPM is able to apply on the environment while maintaining a given pose given force limits imposed on actuator for a given actuator was studied in [20] and [21]

Wrench Closure Workspace WCW is derived from stiemke's theorem in [22] and implemented numerically by interval analysis in [23] [24] [25]

Static Equilibrium conditions for CDPMs are presented in [26] Here we see that an over constrained configuration is important especially in applications where there exists no gravity. This system having more cables than the number of DOF of the moving platform is solved by linear programming as shown in [27] and [28]

Control of CDPMs might be complex due to actuation redundancy.Methods to measure the tension in the cables were proposed in [29] and a controller based on the cable tension was proposed in [30]. Sliding mode control has been applied to CDPMs in [31]

Visual Based servoing has been used to control a CDPR in [32]. Here a CDPM called Marionet-Assist, a mobility assist device which has 3-DOF translation with a camera at its end effector is controlled to grasp a target and move it from one location to another. This control scheme uses photometric moments to ensure a robust control.

Several open-source and licensed Robot simulators exist [33] [1] including Stage, Gazebo, V-Rep, MS-Robotics studio, Robologix, Labview,MATLAB to name a few which are able to recreate the behavior of a robot in software. Some of the requirements for a robotic simulator are:

1. The supported operating system on where the simulator can run.

2. Ability to perform 2D or 3D simulation

3. Supported Programming languages

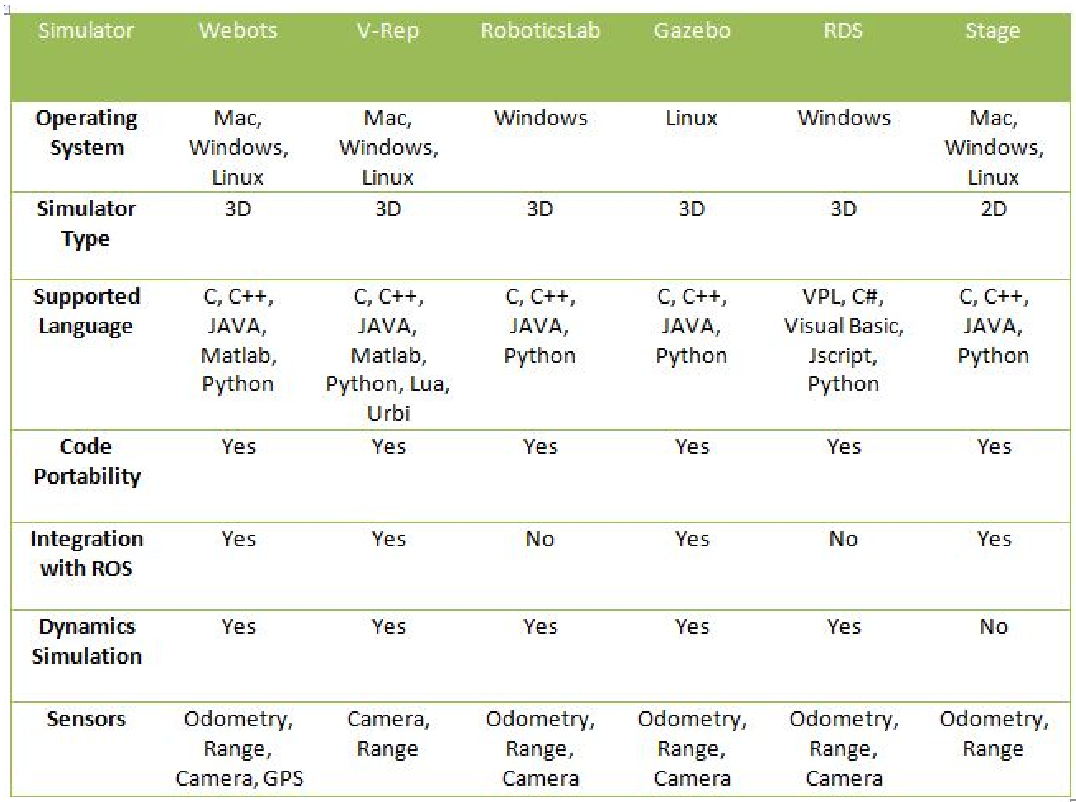
4. Code Portability where we look at how easily we can deploy such a code directly on a real robot.

5. Sensor and sensor support

6. Ability to perform dynamic simulations using rigid body dynamics collisions, obstacles etc.

7. Integration with ROS.

Below we can see a comparison of the capabailities of these software



Simulator	Webots	V-Rep	RoboticsLab	Gazebo	RDS	Stage
Operating System	Mac, Windows, Linux	Mac, Windows, Linux	Windows	Linux	Windows	Mac, Windows, Linux
Simulator Type	3D	3D	3D	3D	3D	2D
Supported Language	C, C++, JAVA, Matlab, Python	C, C++, JAVA, Matlab, Python, Lua, Urbi	C, C++, JAVA, Python	C, C++, JAVA, Python	VPL, C#, Visual Basic, Jscript, Python	C, C++, JAVA, Python
Code Portability	Yes	Yes	Yes	Yes	Yes	Yes
Integration with ROS	Yes	Yes	No	Yes	No	Yes
Dynamics Simulation	Yes	Yes	Yes	Yes	Yes	No
Sensors	Odometry, Range, Camera, GPS	Camera, Range	Odometry, Range, Camera	Odometry, Range, Camera	Odometry, Range, Camera	Odometry, Range

Figure 1.3: Comparison of existing Robot Software

The authors in [34] have made a study among researchers to determine the most preferred choice of software for dynamic simulation and reasons for this choice. From the results of this study, we see that Gazebo is the most preferred software for simulation amongst researchers. These come from the desired criteria such as: a simulation very close to reality, open-source software,ability to use same code for real and simulated robot, light and fast simulator. This study has indeed confirmed our choice of Gazebo to perform this simulation.

The author in [35] has studied the use of a CDPR for the use in Algae Harvesting by performing a simulation to choose the design parameters for such a system. This approach intends to solve the workspace problem of large scale commercial farming of and he performs the simulation of such a system using MATLAB.

Another simulator which has been developed for cable driven parallel robots is *ARACHNIS* [5]. Here, the authors have developed a CDPM simulator using MATLAB for the Analysis of CDPMs. This software is able to generate the WFW Wrench Feasible Workspace and Interference Free Constant Orientation Workspace (IFCOW) of CDPMs for both spatial and planar mechanisms. This software is able to greatly reduce the computation time for the WFW and IFCOW of the cable driven parallel robot which can be quite computationally expensive. But this simulator does not animate the motion of such a mechanism within this workspace or show the structure of the mechanism in an indoor or outdoor environment or take into account the ability to extend the simulation using sensors and interaction with real world objects.

A dynamic simulator for autonomous underwater vehicles has been developed based on gazebo, integrated with ROS and rendered using underwater image rendering software called UWSim [36].The authors have developed plugins that implements the model of the robot, a model for the environment which is underwater and a model for the PID controller.

A simulator for CoGiRo, a CDPM, was developed in [11] as part of the EU-FP7 CableBot project.The authors make use of a 3D CAD software to model the component parts of the CDPR such as winches, pulleys, cables and cable fastening, then the parts are imported to another software called XDE where the simulation is to be performed and assembled as a complete CDPR. This robot assembly is then controlled using Matlab/Simulink interface that implements motion generation, inverse kinematics and PID control of the robot's cartesian platform position.

This Bibliography study will look at:

- The Modeling of Cable Driven Parallel robots
- The use of Gazebo in performing Simulation
- Integration of Sensors and Plugins to the Robot in simulation
- Interfacing our Gazebo simulated robot with ROS

Chapter 2

Modeling of Cable Driven Parallel Robots

In this chapter we discuss the current approach used to carry out the modeling a cable driven parallel robot which has been dealt with in several works of study such as [10] [3] [37], [26], [18].

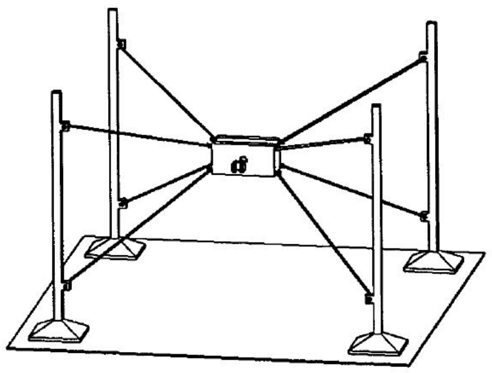
A cable driven parallel manipulator usually consists of a number of cables, which are connected to fixed points and the other end point of these cables are attached to the common end effector. The position and orientation of the end effector is controlled by increase or decrease of the cable lengths achieved by rolling of the spool that holds the total cable length.

If we denote the number of cables that make up the CDPM as m and the number of degrees of freedom of the end-effector as n, then three cases arise [38]:

Case 1 : Incompletely Restrained CDPM - In this case, at least one equation of constraint is still required to determine the pose of the end-effector in any configuration.

Case 2 : Completely Restrained CDPM - In this case $m = n+1$, where the pose of the robot is fully determined by the unilateral kinematic constraints imposed by the cable.

Case 3 : Redundantly Restrained CDPM - In this case $m > n+1$, where the pose of the robot has more unilateral kinematic constraints imposed on it by the cables than required.


(a) An Example of a Redundantly Constrained CDPM [26]

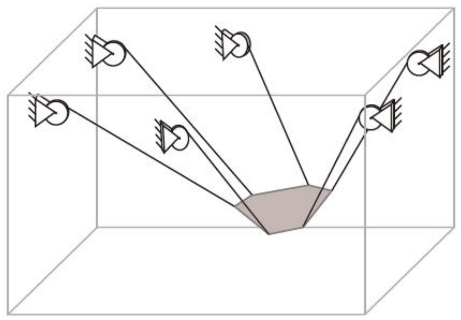

(b) An Example of a Compeletely Constrained CDPM [10]

Figure 2.1: Examples of Cable Driven Parallel Manipulators

From the following, we see that we based on the difference between the number of wires m and number of the degrees of freedom of the end-effector n, the CDPM will have a redundancy given as $r = m - n$.

We note that in both cases, there is an effect on the static and dynamic equilibrium of the CDPM depending on the number of cables used to define the configuration.

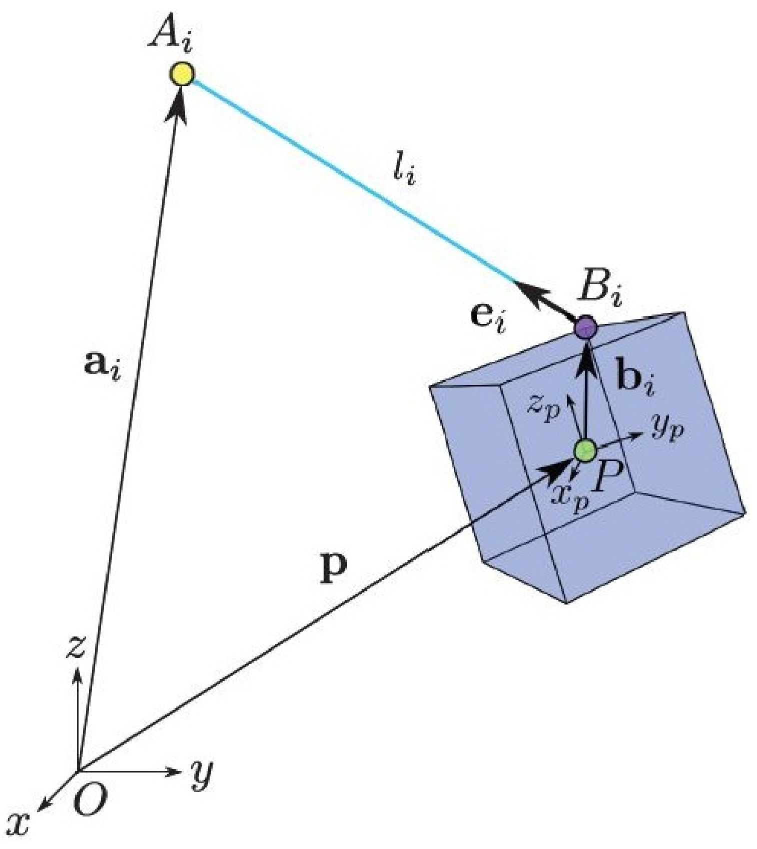


Figure 2.2: Geometric Description of a single cable from Base to End effector of a CDPM [3]

2.1 Geometric Description of CDPMs

A single connection of a CPDM from the fixed base to the end-effector point is described geometrically in 2.2.

From the figure point A_i defines the point on the base where cable i is attached while point B_i defines the point on the end effector where the cable i is attached. From this, we also define the co-ordinates of point A_i to be a vector $\mathbf{a}_i$ which is defined in the Global frame $\mathfrak{R}_{\mathfrak{a}} = \{O, x, y, z\}$.

Usually the base of the CDPM are known points in the room, the global frame will be the frame of the room. We also denote the co-ordinates of point B_i using the vector $\mathbf{b}_i$ which is defined in the local frame of the end-effector $\mathfrak{R}_{\mathfrak{p}} = \{P, x_p, y_p, z_p\}$. From this, we can see that the instantaneous length of the cable i will be given by the relation:

The position and orientation of the end-effector at point p in the global frame can be described by a pose vector $\mathbf{p} = [x, y, z, \phi, \theta, \psi]^T$ for a spatial robot or $\mathbf{p} = [x, y, \theta]^T$ for a planar robot.

The Homogeneous Transformation matrix between the Global frame and the End-effector frames in the spatial case is given as:

$$\mathbf{T} = \begin{bmatrix} c\theta c\psi & -c\theta s\psi & s\theta & x \\ c\phi s\psi + s\phi s\theta c\psi & c\phi c\psi - s\phi s\theta s\psi & -s\phi c\theta & y \\ s\phi s\psi - c\phi s\theta c\psi & s\phi c\psi + c\phi s\theta s\psi & c\phi c\theta & z \\ 0 & 0 & 0 & 1 \end{bmatrix} = \begin{bmatrix} \mathbf{Q}_{3x3} & \mathbf{c}_{3x1} \\ \mathbf{0}_{1x3} & 1 \end{bmatrix} \tag{2.1}$$

whereas in the planar case:

$$\mathbf{T} = \begin{bmatrix} c\theta & -s\theta & x \\ s\theta & c\theta & y \\ 0 & 0 & 1 \end{bmatrix} = \begin{bmatrix} \mathbf{Q}_{2X2} & \mathbf{c}_{2x1} \\ \mathbf{0}_{1x2} & 1 \end{bmatrix} \tag{2.2}$$

In both cases, matrix, $\mathbf{Q}$ defines the rotation matrix and vector $\mathbf{c}$ is a vector of the position of the center of the end-effector.

The orientation in spatial case is represented by ϕ, θ, ψ given by the Euler angles obtained first by a rotation ϕ about the z-axis, followed by a rotation θ about the $x-axis$ and finally a rotation of ψ around the $y-axis$.

In the planar case, the angle θ is given by the angle between the $x-axis$ of the robot frame and the $x-axis$ of the frame attached to the end effector

2.2 Inverse Kinematics

From the geometric description that we have given in the previous section, we see that the length of the cable at any instant is given as

$$\mathbf{l}_i = \mathbf{a}_i - \mathbf{c} - \mathbf{Q}\mathbf{b}_i \tag{2.3}$$

The length of the cable i is the norm of $\mathbf{l}_i$

$$l_i = \|\mathbf{l}_i\|_2 \quad 1 \le i \le m \tag{2.4}$$

The vector $\mathbf{l}$ is a vector of cable lengths:

$$\mathbf{l} = [l_1 \; l_2 \; ... \; l_m]^T \tag{2.5}$$

The Inverse kinematics of a cable-driven parallel manipulator gives the relationship between the speed of the cables $\dot{\mathbf{l}}$ and the twist of the moving platform $\mathbf{t}$

$$\dot{\mathbf{l}} = \mathbf{J}\mathbf{t} \tag{2.6}$$

where

$$\mathbf{J}_{mxn} = \begin{bmatrix} -\mathbf{d}_1^T & (\mathbf{d}_1 \text{ x } \mathbf{Q}\mathbf{b}_i)^T \\ -\mathbf{d}_2^T & (\mathbf{d}_2 \text{ x } \mathbf{Q}\mathbf{b}_2)^T \\ \vdots & \vdots \\ -\mathbf{d}_n^T & (\mathbf{d}_n \text{ x } \mathbf{Q}\mathbf{b}_n) \end{bmatrix} \tag{2.7}$$

$$\dot{l} = [\dot{l_1} \; \dot{l_2} \; ... \; \dot{l_n}]^T \tag{2.8}$$

where : $\hat{\mathbf{l}}_i$ is the normalized vector of the cable length which is given as

$$\mathbf{d}_i = \frac{\mathbf{l}_i}{\|\mathbf{l}_i\|_2} \tag{2.9}$$

2.3 Static Equilibrium

The static equilibrium of a cable-driven parallel manipulator is closely related to its inverse kinematics [26]. This relationship makes use of the transpose of its Kinematic Jacobian to write:

$$\mathbf{W}\mathbf{f}_a + \mathbf{f}_p = \mathbf{0} \tag{2.10}$$

The proof of this can be derived from the principle of virtual work as shown in [3]. Where: $\mathbf{f}_a$ represents the mx1 vector of positive tension in the cables of the parallel robot.

$$\mathbf{f}_a = \begin{bmatrix} f_{a1} & f_{a2} & \cdots & f_{am} \end{bmatrix}^T \tag{2.11}$$

This value is usually limited within a mechanical range conforming to the maximum load of the cable and the elastic limit beyond which the cable can no longer hold.

$$f_{min} \le f_{ai} \le f_{max} \tag{2.12}$$

Another condition is that that the vector of cable tensions only admits positive values and must be non-negative

$$f_{ai} > 0 \tag{2.13}$$

$\mathbf{f}_p$ represents the represents the nx1 vector forces and moments acting on the end-effector of the CDPM.

$$\mathbf{f}_p = [\mathbf{f}^T\ \mathbf{m}^T]^T \tag{2.14}$$

This vector could be composed of gravitational forces which is acting on the robot end effector or other external contact forces that act on the end effector.

$$\mathbf{W} = -\mathbf{J}^T \tag{2.15}$$

This matrix is used to study the static equilibrium of the robot since by physical relations[26] :

The meaning of (2.10) is that the sum of all wrenches acting on the CDPM must be equal to zero to achieve static equilibrium configuration. We will see that there exists some desired pose in the workspace for which the CDPM cannot achieve static equilibrium and this is major due to the conditioning of the wrench matrix at this pose.

The matrix $\mathbf{W}, nxm$ is popularly called the *wrench matrix* and is dependent on the pose of the cable- driven parallel robot. In a completely constrained cable-driven parallel manipulator, the wrench matrix is not square and the inverse solution is usually obtained by a generalized inverse written as:

$$\mathbf{W}^+ = \mathbf{W}^T(\mathbf{W}\mathbf{W}^T)^{-1} \tag{2.16}$$

or by minimization for the appropriate cable tensions $\mathbf{f}_a$ to hold the robot in the static configuration at a given pose while satisfying all the cable tension conditions [18] [26].

$$min\ \ \mathbf{f}_a^T\mathbf{f}_a \begin{cases} \mathbf{W}\mathbf{f}_a = \mathbf{f}_p & (2.10) \\ \mathbf{f}_{ai} > 0 & (2.13) \end{cases}$$

2.4 Dynamics of Cable Driven Parallel Robot

We will consider the dynamic modeling of a CDPM whose cables are assumed to have negligible mass and are not elastic. With this assumption, the dynamics is reduced to only that of the end effector and is given as

$$\mathbf{M}\dot{\mathbf{t}} + \mathbf{C}\mathbf{t} + \mathbf{f}_g = \mathbf{W}\mathbf{f}_a \tag{2.17}$$

where : $\mathbf{M}$ is the mass matrix of the robot, $\mathbf{f}_g$ is a vector of the gravity terms,$\mathbf{Ct}$ gives the Coriolis and centrifugal terms.

$$M = \begin{bmatrix} mI_p & \mathbf{0}_{pxq} \\ \mathbf{0}_{qxp} & \mathbf{K} \end{bmatrix} \tag{2.18}$$

where p = No of Translational DOF in the pose vector and q = No of rotational DOF of the pose vector, m is the mass of the moving platform, I_p denotes a p x p identity matrix. $\mathbf{f}_g = [0\ 0\ -mg\ 0\ 0\ 0]^T$

$$\mathbf{Ct} = \begin{bmatrix} \mathbf{0}_{nx1} \\ \omega \text{x} \mathbf{K}\omega \end{bmatrix} \tag{2.19}$$

The actuator dynamics is given as:

$$\mathbf{I}_m\ddot{\mathbf{q}} + \mathbf{f}_m(\dot{\mathbf{q}}) + \mathbf{R}\mathbf{f}_a = \tau_m \tag{2.20}$$

where $\mathbf{q}$: joint angles of the motor shaft, $\mathbf{I}_m$ m x m Diagonal Positive Inertia Matrix of the Actuator, $\mathbf{R} = diag[r_1,\ r_2,\ .\ .\ .,\ r_m]$ given that r is the radius of the pulley, $\mathbf{f}_a$ is the vector of cable tensions and τ_m is the m x 1 vector of motor torques, $\mathbf{f}_m$ is the m x 1 vector of friction for each of the motor. $\mathbf{K} = \mathbf{Q}\mathbf{I}_p\mathbf{Q}^T$ is the inertia matrix of the end-effector expressed at the reference point, P in the global frame with I_p being the inertia matrix of the end-effector expressed in the local end-effector frame.

$$\dot{\mathbf{q}} = \mathbf{R}^{-1}\dot{\mathbf{l}} \tag{2.21}$$

$$\dot{\mathbf{l}} = \mathbf{J}\mathbf{t} \tag{2.22}$$

we can obtain the relationship between the torques in the motor and the end effector as below by substituting for the motor shaft velocity and differentiating with respect to time to obtain the motor joint acceleration.

$$\ddot{\mathbf{q}} = \mathbf{R}^{-1}\mathbf{J}\dot{\mathbf{t}} + R^{-1}\dot{\mathbf{J}}\mathbf{t} \tag{2.23}$$

substituting for $\mathbf{f}_a$ we finally obtain the full dynamic model as:

$$\mathbf{M}\dot{\mathbf{t}} + \mathbf{C}\mathbf{t} - \mathbf{f}_g = \mathbf{W}\mathbf{R}^{-1}(\tau_{\mathbf{m}} - (\mathbf{I}_m\ddot{\mathbf{q}} + \mathbf{f}_m(\dot{\mathbf{q}}))) \tag{2.24}$$

2.5 Stiffness of a Cable-Driven Parallel Robot.

A goal in the design of CDPM is to have a high stiffness such that the robot has a small displacement to an external wrench. The cable tensions and the cable stiffness contribute to the total stiffness of the CDPM and enable the robot to resist an external wrench applied on it.The stiffness Matrix of a CDPM provides a relationship between an external wrench acting on the robot and infinitesimal displacement of this robot [39].

In static equilibrium, an external wrench $\mathbf{f}_p$ acting instantaneously at the end effector, the instantaneous change in the pose d$\mathbf{p}$. It can be obtained by taking a derivative of $-\mathbf{f}_p$ with respect to the pose $\mathbf{p}$ and substituting the relationships (2.10) and (2.15).

$$\mathbf{K} = -\frac{d\mathbf{f}_p}{d\mathbf{p}} = \mathbf{J}^T\frac{d\mathbf{f}_a}{d\mathbf{p}} + \mathbf{f}_a\frac{d\mathbf{J}^T}{d\mathbf{p}} \tag{2.25}$$

From (2.22)

$$\frac{d\mathbf{f}_a}{d\mathbf{p}} = (\frac{d\mathbf{f}_a}{d\mathbf{l}})\frac{d\mathbf{l}}{d\mathbf{p}} = \mathbf{J}\frac{d\mathbf{f}_a}{d\mathbf{l}} \tag{2.26}$$

$$\mathbf{K} = \mathbf{J}^T\Omega\mathbf{J} + \mathbf{f}_a\frac{d\mathbf{J}^T}{d\mathbf{p}} \tag{2.27}$$

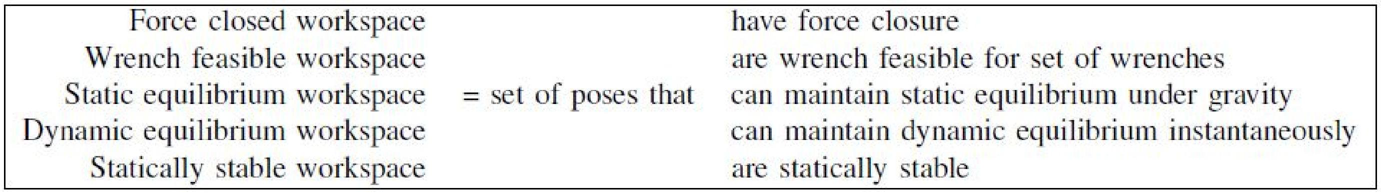
$$\Omega = \frac{d\mathbf{f}_a}{d\mathbf{l}} = diag(\ k_1,\ k_2, .\ .\ .\ k_m) \tag{2.28}$$

where k_i represents the individual stiffness of the cable i, it is a function of the elasticity of the cable

2.6 Workspace of CDPRs

The workspace of a cable driven parallel robot has been a subject of research from several authors [40] [24] [18] [4]. Cable-driven parallel robots generally have a large workspace since the length of the cables are limited by the dimensions of the room in theory. The application that we will use the robot will also require that we exert specific forces and moments at different parts of the workspace. The important workspaces of a cable-driven parallel robot are:

1. : The Wrench Feasible Workspace (WFW).
2. : The interference-free constant orientation workspace (IFCOW).
3. : Force Closure Workspace



Force closed workspace		have force closure
Wrench feasible workspace		are wrench feasible for set of wrenches
Static equilibrium workspace	= set of poses that	can maintain static equilibrium under gravity
Dynamic equilibrium workspace		can maintain dynamic equilibrium instantaneously
Statically stable workspace		are statically stable

Figure 2.3: Definitions of the different types of Workspaces of a CDPR [4]

2.6.1 The Wrench Feasible Workspace (WFW)

The wrench feasible workspace is a set of poses for a CDPR where a wrench or a set of required wrenches can be applied to the end-effector can be counteracted by tension forces in the cables. We note that the wrenches are always non-negative since the cables can apply forces to the end-effector in one direction and these wrenches lie within an admissible range since the cables have a stress limit.

Mathematically, WFW corresponds to every pose of the robot where (2.10) can be satisfied and thus is dependent on the wrench matrix W. This determines the types of wrenches that the robot applies to the environment and therefore determines the application for which the robot can be used.

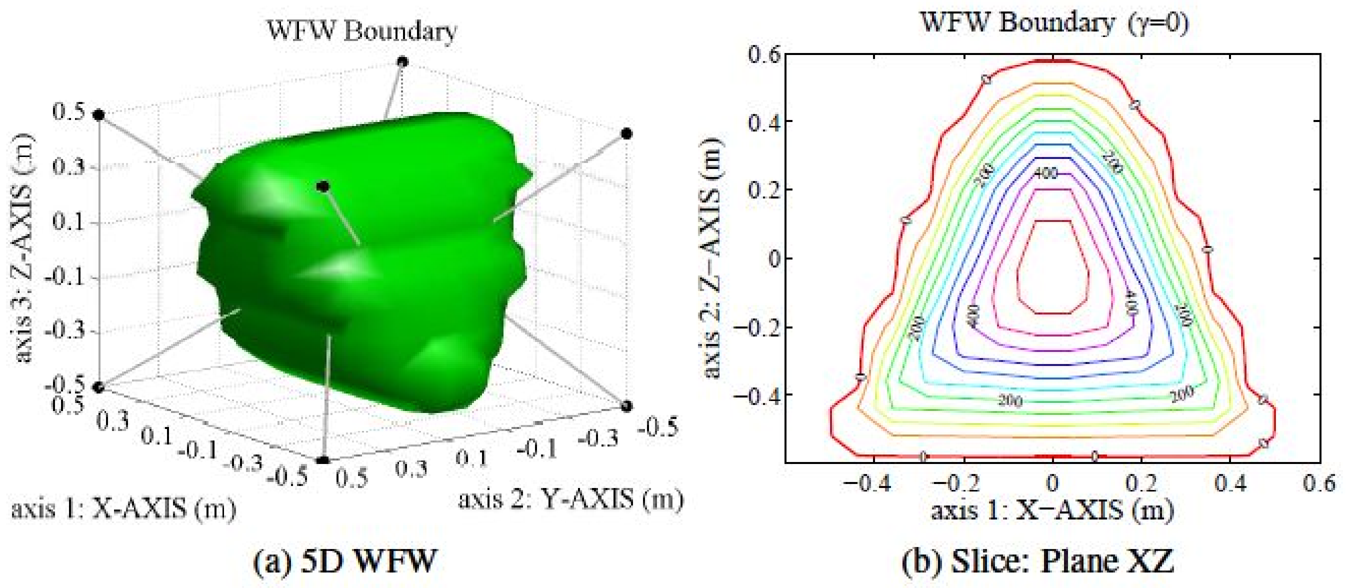


Figure 2.4: Wrench Feasible Workspace of a spatial CDPR as obtained from *ARACHNIS* [5]

WFW can be observed in two cases :

1. : Static Equilibrum Workspace: This is defined as the set of poses for which the end-effector can be balanced by non-negative cable tensions with no external forces on the end-effector except gravity. Here the only forces acting on the robot come from the weight of the cable and the weight of the end-effector

2. : Dynamic Equilibrum Workspace: This is defined as the set of poses for which any instantaneous load attached to the moving platform can be balanced by the non-negative cable tensions.

2.6.2 The interference-free constant orientation workspace (IFCOW)

This is characterized by the set of poses where there is no interference between the cable to another cables or between the cables and the end-effector with a fixed-orientation.

2.6.3 Force Closure Workspace

This is a pose of the cable-driven parallel robot where any arbitrary external wrench applied to the end-effector can be counter balanced by non-negative cable tensions.

Several methodologies have been proposed to obtain the different workspaces of a cable-driven parallel robot:

[24] proposes the use of interval arithmetic to analyze a box of poses to determine conditions in which the box of pose could lie either fully inside the WFW or fully outside the WFW.

WFW can also be determined by a discretization to obtain a grid of end-effector poses and testing each pose for wrench-feasibility using a search or 'brute-force' [41] or analytically for point, spatial and planar cable driven parallel robots as has been done in [40].

[42] proposes an algorithm to calculate an interference between a cable of a CDPR and another cable of the same robot and also another algorithm to calculate an interference between the cable

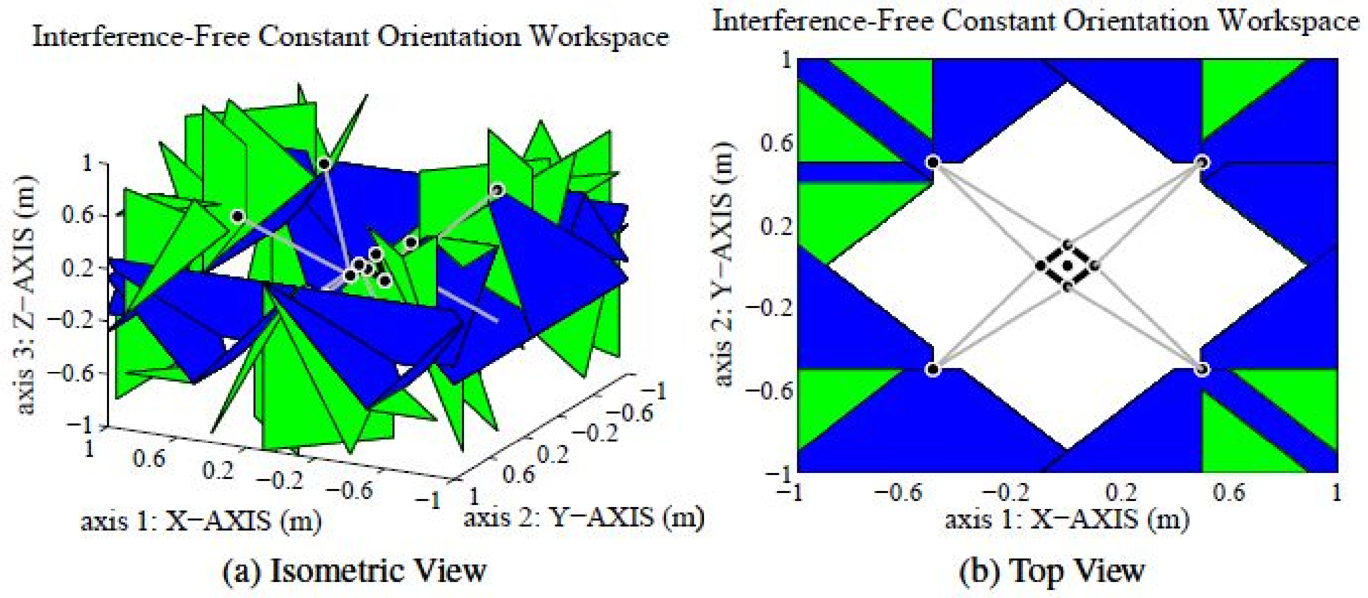


Figure 2.5: interference Free Constant Orientation Workspace of a planar CDPR as obtained from *ARACHNIS* [5]

But more recently in [5], a software called *ARACHNIS* has been developed which is able to perform the fast computation of the wrench-feasible workspace and Interference-Free Constant Orientation workspace for a particular CDPR when we provide the parameters describing the robot. This software will be very useful in design.

Chapter 3

The Gazebo Simulator

What is Gazebo?

Gazebo is a 3D dynamics simulator used in testing robotic applications and scenarios [6]. This enables developers to evaluate and test a robot or several robots quickly and in realistic conditions without damaging the actual robot Gazebo development began in the fall of 2002 at the University of Southern California. Originally, Gazebo was developed to be used to test robot algorithms but today, it has evolved adding further functionalities such as:

- Dynamics Simulation
- Visualization of 3D Graphics
- Integration of Sensors and Noise to the Robot
- Ability to add plug-ins to test your model
- Some readily available robot models
- Cloud Simulation and Command Line tools.

The current version of gazebo at the time of this publication is *version* 6.0.0. It is free, open-source and very popular within the robotics community. Gazebo is currently funded by DARPA and maintained by OSRF Foundation.

3.1 Physics Engine

The physics Engine is used by gazebo to simulate the dynamics and kinematics of rigid bodies, tests for collisions. Gazebo is able to use different physics engines to perform the simulation.ODE [43] is the default physics engine used, but there exist other physics engines that can be integrated to gazebo based on the users choice such as Bullet, Simbody, DART.

3.2 OpenGL

OpenGL/GLUT work together in gazebo to provide the user interface and visualization for gazebo [44]. OpenGL is a platform independent library for rendering 2D and 3D scenes the rendering of the simulation at the front-end. This used to generate Images of the Simulation for the Graphical User Interface (GUI) or for camera sensors within the simulation. Scenes that are created in OpenGL are displayed on the screen by GLUT.

3.3 Architecture

The gazebo program runs in a client-server architecture which can be depicted in the figure shown:The server then receives data and control commands from the client through a shared memory interface.

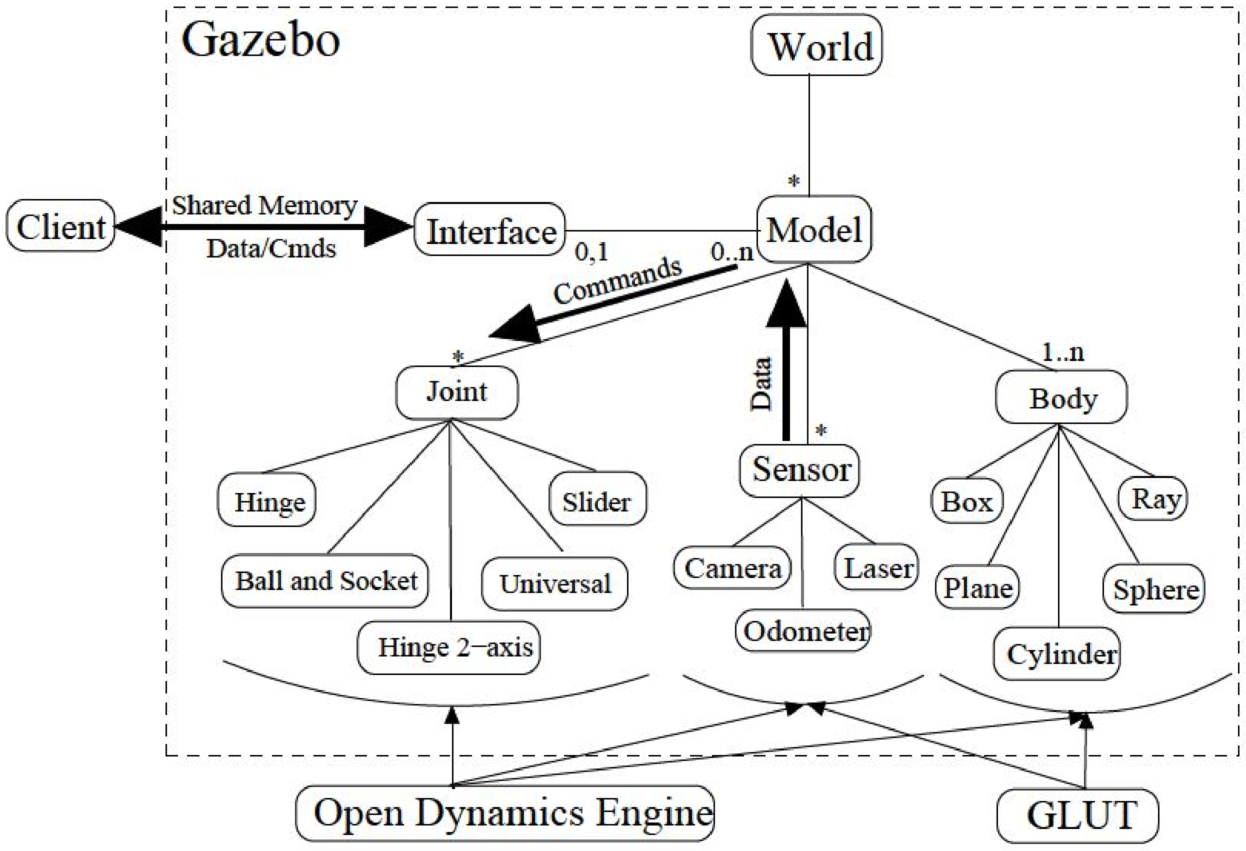


Figure 3.1: Architecture of Gazebo [6]

3.3.1 Models

The world contains all the sensors, joints and links that can be put together to construct a real device or robot. These include basic physical shapes such as a box, cylinder, sphere or other physical aspects such as ray of light, hill etc. These models are defined using a Simulation Definition format (SDF)

A "link" is a rigid body that moves as a whole. A link contains three main sets of properties:

- Inertial Parameters : These defines the mass and inertia used to calculate the dynamics of the object.
- Collision: Defines the physical space occupied by the object and checks when the object collides with another object or the environment
- Visualization: Used to show the object on the screen or to make it possible to capture the object in a vision sensor

A "joint" holds together two links, constraining their motion. A joint may have limits. We can choose from different types of joints available e.g. universal joint, spherical joint etc to include in our model of a cable driven parallel robot.

The sensors could the different types of sensors available such as a camera, laser range finder etc.

Objects in gazebo can be static or dynamic. Static Objects are those that cannot move but can only collide and are defined by setting the tag in the sdf file as $< static > true < /static >$

Dynamic Objects are those that can move, have an inertia and can collide, they are set by removing the $< static >$ tag.

3.4 SDF

Simulation Description Format ,SDF,is an XML file that describes objects and environments for robot simulators, visualization, and control [45]. It is an extension of the URDF format that is used in ROS with an improvement of the ability to define Lightning, Outdoor environments etc. A big advantage of Gazebo over ROS is that Gazebo uses SDF which supports closed kinematic chains meaning that we can use it for parallel robots, ROS uses URDF which does not support closed kinematic chains.[46]

3.5 Using Gazebo with ROS

ROS(Robot Operating System) [47] is an open-source middle-ware that contains tools for building and testing robotics applications. It has a lot of plug-ins, libraries and source code that we can easily use from the repository to integrate with the gazebo simulator.

Integration of our Gazebo simulator with ROS gives us access to a wide range of user contributed algorithms making development faster and more focused.

Older versions of Gazebo were included inside of ROS as one of its packages but today Gazebo operates as a standalone software and has no direct dependencies on ROS. The interest in ROS comes from the fact that we can use already defined robot models and robot algorithms that exist in ROS through meta-package called gazebo_ros_pkgs.

3.5.1 ROS nodes

These are a collection of largely independent but interacting software processes which are able to communicate with each other using predefined message types.These nodes can be added or removed as long as they follow specific rules to communicate their information. They could be written in C/C++, Python, LISP, MATLAB or Java. The two central process in the ROS frame work is the **Roscore** which manages all processes and communication between processes.

The parameter server is used to holds parameters centrally to ensure that when two different software processes share data, get the same information while providing a means to store and retrieve software parameters without having to change code.

ROS Topics and Services

Nodes in ROS can run and produce information, this information or data is advertised over a **Topic** such that another process or software willng to use such information could subscribe to this topic and receive this data at each cycle.

Within ROS, two different software processes, e.g a process that requests for an Inverse kinematic solution and another process that performs the Inverse Kinematics solver will communicate using using a **rosservice**.ROS topics and services There are two basic means for communication between ROS node.

ROS Messages

ROS defines message types which are structures containing data of different types such as integers, strings, time etc, that can be passed between nodes but we are also free to create out own message type depending on our needs. For example, we can use a PID controller to compute Joint torques but we will compose this torque into a Message vector including a time stamp and this ros node will send this torque as a message to a robot simulation model in gazebo.

ROS has a very active and collaborative user community and is at the frontier of Robotics software. There are also tutorials, wiki pages, support forums and periodical conferences organized by

ROS was initially developed at Stanford Artificial Intelligence Laboratory, today ROS is maintained by OSRF Foundation.

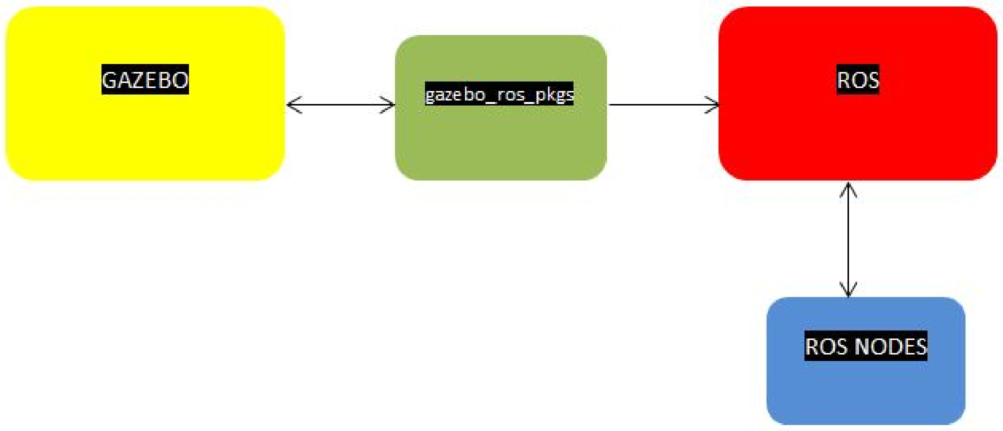
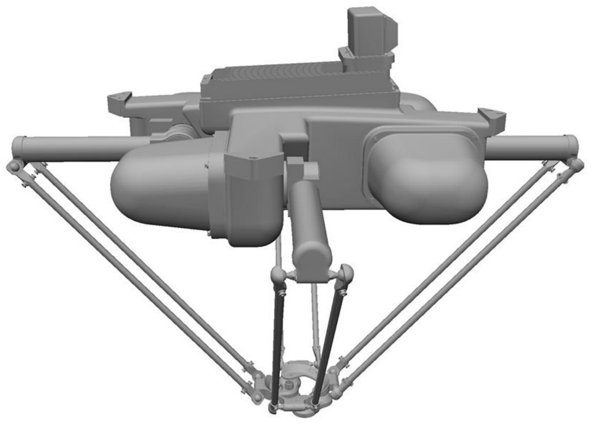


Figure 3.2: Figures Showing the Relationship between Gazebo and ROS [7]

3.6 3D Models

Gazebo can be used to create simple objects, links and basic shapes from the SDF file definition. In the case where we require more complex 3D shapes or models composed of several objects, its is more desirable to create such an object with a robotic 3D CAD modeling software such as *solidworks*, we then format this model as *.stl* or *.collada* files and then import these files into gazebo
This approach makes model development and testing faster, easier and more realistic. Below we see some examples of 3D models that have already been created of Parallel robots that can be imported to Gazebo:


(a) Adept Robot

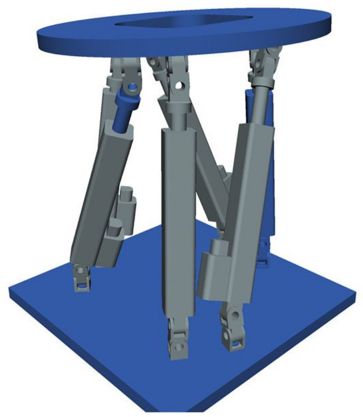

(b) GoughStewart Platform

Figure 3.3: 3D models of some Parallel Robots [8]

3.7 3D Model Repositories

There exists several repositories that hold 3D models of different objects such as Blender, Sketchup, Google 3D warehouse [48]. From these repositories, we can define and import 3D models of the objects or environment that we want to simulate and import them into gazebo.
Gazebo also allows us to import from 3D repositories where the designer can access already created models of objects and already created models of the environment making the simulator development faster. In this way we do not have write from the beginning all that is required to create our simulator, we could simply reuse and edit a model from the repository and incorporate it into the simulator.
In our case,we will have to create the 3D Model of a cable driven parallel robot and then import the 3D model into gazebo in order to have a simulation that is as accurate as possible.

3.8 Advantages of using Gazebo

- Ability to define completely our robot in 3D software.
- Simulation of commonly used sensors such as laser ranger finders, GPS, Pan-Tilt-Zoom cameras etc,
- It also has some predefined robot models such as Pioneer2DX, PR2, Care-O-Bot Robot, Kobuki Robot, Nao Humanoid, robot.
- This is also a free software and thus helps us to reduce the development costs.
- We can include several robots in our simulation, add, remove or change our environment and models,
- We can also use the physics engine that simulates the behavior of materials
- It runs on Linux and can integrate plug ins written in C++/C/Python programming language
- We can take advantage of the resources such as models, source code and plugins for devices that exist within ROS using the gazebo_ros_pkgs bridge.

3.9 Installation

Currently, only the Ubuntu distribution is supported on SDF library, thus it is adviceable to perform this simulation development on Ubuntu platform. This covers installation for Gazebo *version*5.0.0 that has been made on ubuntu 14.04 LTS version operating system with the computer connected to the Internet. For installation on older versions of ubuntu, see installation guide at [7].

3.9.1 ROS Installation

1. On the linux terminal we type or paste the following lines one after the other:list

```
sudo sh -c 'echo "deb http://packages.ros.org/ros/ubuntu $(lsb_release -sc) main" > /etc/apt/sources.list.d/ros-latest.list'

sudo apt-key adv --keyserver hkp://pool.sks-keyservers.net:80 --recv-key 0xB01FA116

sudo apt-get update; sudo apt-get install ros-jade-desktop-full

sudo rosdep init
rosdep update

echo "source /opt/ros/jade/setup.bash" >> ~/.bashrc
source ~/.bashrc
```

3.9.2 Gazebo Installation

1. On the linux terminal we type or paste the following lines one after the other:

```
wget -O /tmp/gazebo5_install.sh http://osrf-distributions.s3.amazonaws.com/gazebo/gazebo5_install.sh; sudo sh /tmp/gazebo5_install.sh
export GAZEBO_MODEL_PATH=~/.gazebo/models:$GAZEBO_MODEL_PATH
export GAZEBO_RESOURCE_PATH=/usr/share/gazebo-2.2:$GAZEBO_MODEL_PATH
source ~/.bashrc
sudo apt-get install ros-indigo-gazebo-ros-pkgs
```

3.9.3 Catkin Workspace

1. : We setup the catkin workspace which is a folder within which we will work

```
mkdir -p ~/catkin_ws/src
cd ~/catkin_ws/src
catkin_init_workspace
cd ~/catkin_ws
catkin_make
echo "source /home/user_name/catkin_ws/devel/setup.bash" >> ~/.bashrc
source ~/.bashrc
```

3.10 Developing Models

A model is dynamically loaded into gazebo during simulation by programming or by selecting it from the GUI. Gazebo has an online database where models contributed by a community of designers are stored and can be accessed. This can be cloned from a linux terminal by:

```
hg clone https://bitbucket.org/osrf/gazebo_models
```

Every Model is created to conform to a specific file structure as shown below:

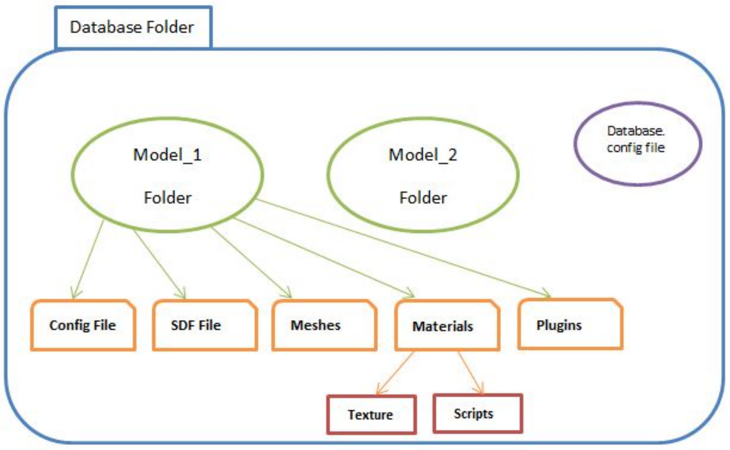


Figure 3.4: Database Structure for a Gazebo Model

1. The database.config contains the metadata about the database and is only required if we want to store our model in the online repository.

2. model.config is an xml file that contains the metadata about the model itself such as the name of the model and the author.

3. model.sdf contains the Simulator description format of the model .

4. meshes is a directory where we put .dae or stl files of 3D models

5. plugins is a directory where we keep source files and header files for plugins.

6. The materials directory contains the texture folder which holds images of the model (jpg, png)and scripts folder where we can find material scripts.

Creating the World

We will create an empty world with with ground plane, light source.

1. Inside gazebo_ros_pkgs folder create a tutorial.world file and paste the following inside:

```
?xml version="1.0" ?>
<sdf version="1.4">
<world name="createWorld">
<include>
<uri>model://sun</uri>
</include>
<include>
<uri>model://ground_plane</uri>
</include>
```

Add Obstacles

We will add some obstacles to the empty world file.

1. Inside the tutorial.world file and paste the following inside:

```
   <model name="barrierA">
   <include>
   <uri>model://jersey_barrier</uri>
   <pose> 2 0 0 0 0 0</pose>
   <static>true</static>
   </include>
   </model>
   <model name="barrierB">
   <include>
   <uri>model://jersey_barrier</uri>
   <pose> 0 2 0 0 0 1.2</pose>
   <static>true</static>
   </include>
   </model>
```

Import a Created Model

For this demonstration, we will add a previously existing robot model in gazebo which closely represents a single cable.

1. Inside the tutorial.world file and paste the following inside:

```
    <!-- Import a Fire hose -->
    <include>
    <uri>model://fire_hose_long</uri>
    <pose>0 0 5 0 45 0</pose>
    </include>
```

Adding a Sensor to a Model

We will add a hokuyo laser sensor to the cable that we have added previously, we define the pose of this sensor and attach it to the cable using a joint.

1. Inside the tutorial.world file and paste the following inside:

```
<include>
<uri>model://hokuyo</uri>
<pose>0 0 6 0 0 0</pose>
</include>
<joint name="hokuyo_joint" type="revolute">
<child>hokuyo::link</child>
<parent>fire_hose_long :: nozzle</parent>
 </joint>
 </world>
 </sdf>
```

Make sure the tutorial.world file amd then launch it on gazebo by typing on the terminal:

1. Inside the tutorial.world file and paste the following inside:

```
 gazebo tutorial.world
```

see something similar to:

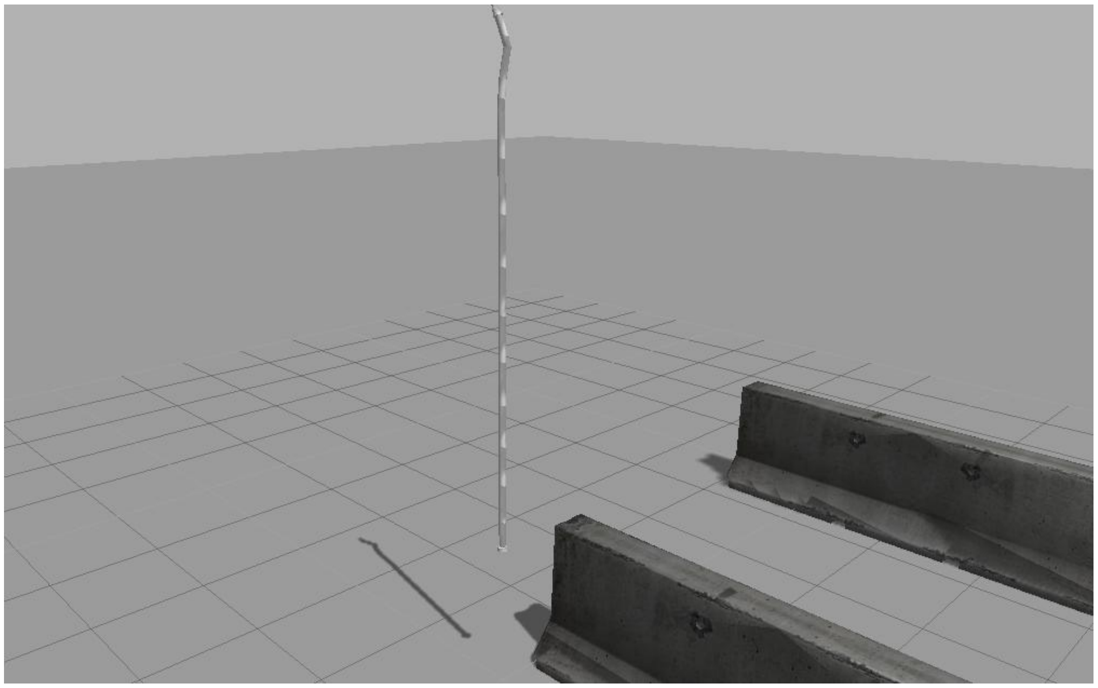


Figure 3.5: An example of Modelling of a cable in Gazebo

3.10.1 Adding a Plugin to a model

A plugin is a C++ code or algorithmn designed to perform a specific task. We can use such code to solve robot kinematics, implement a robot controller and send information from one robot to another. Plugins enable us to choose exactly what to include in our model in order to obtain a specific desired behaviour. They are very flexible since they enable us to alter the program in simulation, rather than being compiled statically. Using plugins in Gazebo also enables a quick sharing of code. There are 5 types of plugin in gazebo:

1. World plugin which is attached to the world
2. Model plugin which is attached to a particular model, e.g a robot
3. Sensor plugin which is attached to a sensor to define the behaviour of such a sensor
4. System plugin which is loaded during startup in the command line.
5. Visual plugins for the rendering

1. Here we show an example of where a plugin is added to a robot model. The plugin is identified by a plugin name and the file name which ends in **.so**. We can optionally add parameters if they are required by the plugin. we can refer to [9] for an example of how a plugin is created in C++

```
<model name="your_robot_model">
<plugin name="differential_drive_controller" filename="libdiffdrive_plugin.so">
... plugin parameters ...
</plugin>
</model>
```

3.10.2 Integrating with with ROS

Gaebo used to be a ROS package but now it runs as a stand-alone package with no dependencies on ROS. The main contact point between gazebo and ROS is through the plugins. We are able to create gazebo plugins through C++ classes that have been predefined in ROS. Then we an compile these plugins, add them to our world file and launch them as a ROS package from the catkin folder. The process flow is shown below:

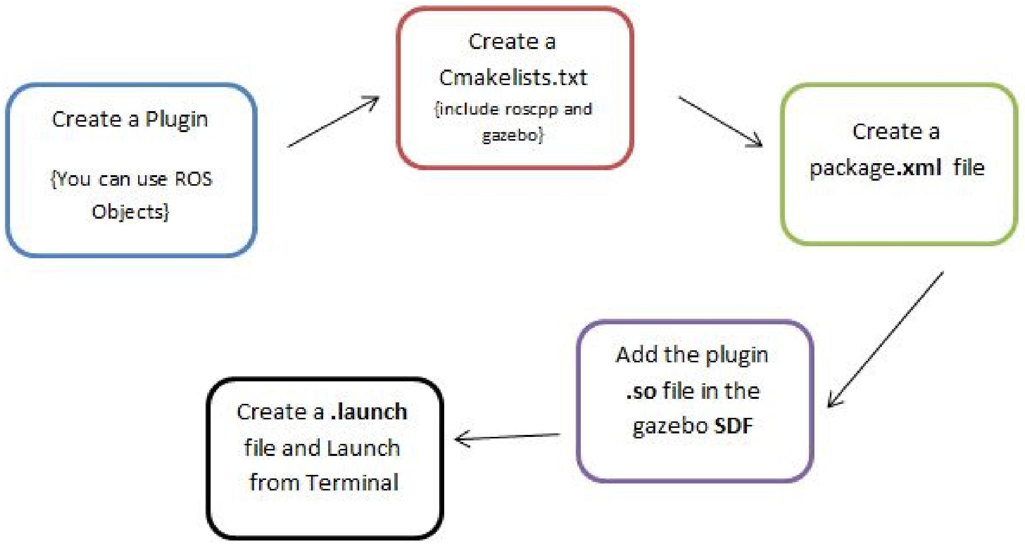

Create a Plugin
{You can use ROS Objects}
Create a Cmakelists.txt
{include roscpp and gazebo}
Create a package.xml file
Add the plugin .so file in the gazebo SDF
Create a .launch file and Launch from Terminal

Figure 3.6: Process flow of using Gazebo and ROS together [9]

3.11 Performance Issues

The Dynamics accuracy is affected by the parameters used in the physics engine and the accuracy of the robot models.

It is therefore important that we note the following points [49] :

1. Choice for the correct step size that will be used to solve the dynamics.
2. Choice for the correct number of iterations in order to obtain a bounded system.
3. Ability to represent as close as possible the real robot in software. The effect of this could be a trade off between having a good visualization and having a fast simulation.
4. Such things as improper joint placement, wrong inertial values or wrong initial positioning of the robot can affect the simulation and should be defined with care.
5. We could have a robot model disappear within the simulation environment due to large accelerations. Such a scenario appears when the force applied to the robot is much greater than it's mass.
6. We could also have a Jittery model if there is a very large ratio between the mass of two connected links. This comes from the stiffness naturally present in such a configuration.

Chapter 4

Conclusion on Proposed Work

In the first chapter of this paper, we have made a review of existing work that has been done in the study of cable driven parallel robots and a general review of some examples of where simulators have been developed in the study of robots.

In the second chapter, we have studied the methodology used in several scientific works to model of cable driven parallel robots. We also looked at the definition of the stiffness of the CDPMs and how the various workspaces are defined.

The third chapter was dedicated to the study of the software aspects of the work specifically gazebo simulator, the major components of gazebo, the methodology used for implementing a simulator with gazebo and how it is used within the ROS framework. We also looked at several advantages that we can get from using this software framework

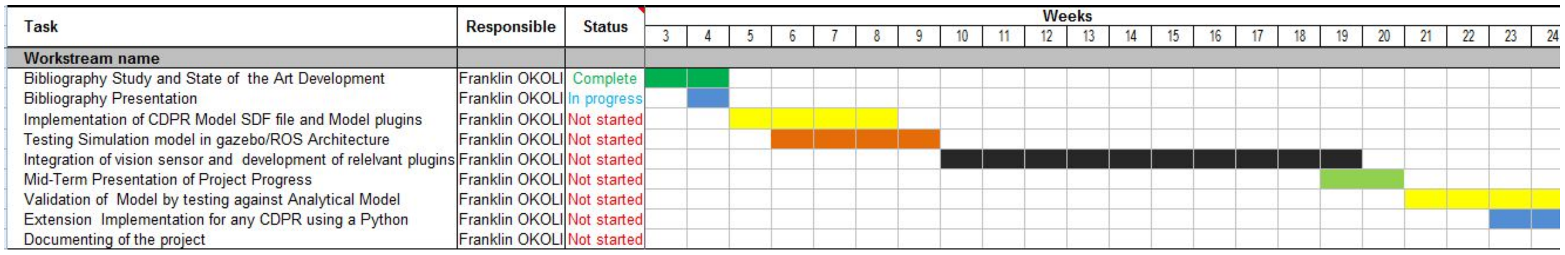
In this chapter four we conclude with the expected implementation of the project. Some Objectives that have be met are :

1. Develop a methodology that can be used to describe a cable in gazebo software.
2. Creating the SDF file file to describe the robot's construction using the cable developed in the previous step and other robot parts including some kinematic parameters.
3. Then we import the model into gazebo for simulation, this step will include application of wrenches to the CDPM and study of the dynamic behavior
4. We also propose to integrate a vision sensor to the robot and develope some plugins for the model.
5. Compare the model developed in Gazebo to an Analytical Model of the system to see the degree of the Modeling error

All programming will be done in C++ and python for the plugins and XML for the SDF files using the ROS framework. We will use libraries available in gazebo and ROS.

4.1 Work Plan

The work plan is as shown below:



Task	Responsible	Status	Weeks																					
			3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
Workstream name																								
Bibliography Study and State of the Art Development	Franklin OKOLI	Complete	🟩	🟩																				
Bibliography Presentation	Franklin OKOLI	In progress		🟦																				
Implementation of CDPR Model SDF file and Model plugins	Franklin OKOLI	Not started			🟨	🟨	🟨	🟨																
Testing Simulation model in gazebo/ROS Architecture	Franklin OKOLI	Not started				🟧	🟧	🟧	🟧															
Integration of vision sensor and development of relelvant plugins	Franklin OKOLI	Not started								⬛	⬛	⬛	⬛	⬛	⬛	⬛	⬛	⬛	⬛					
Mid-Term Presentation of Project Progress	Franklin OKOLI	Not started																	🟩	🟩				
Validation of Model by testing against Analytical Model	Franklin OKOLI	Not started																			🟨	🟨	🟨	🟨
Extension Implementation for any CDPR using a Python	Franklin OKOLI	Not started																					🟦	🟦
Documenting of the project	Franklin OKOLI	Not started																						

Figure 4.1: Work Plan of the Project

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