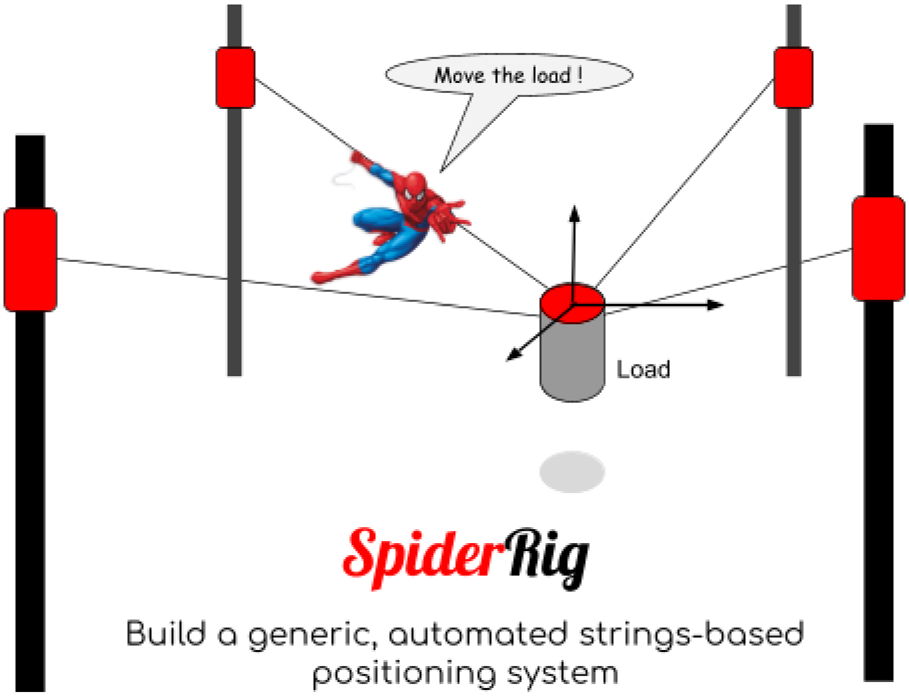

Milestone 2

DESIGN CONSIDERATIONS WORKING DOCUMENT
VR applications

<--- Milestone 1 follow link

project page || join project

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This is a *cocreative-type* document. If you contribute **make sure you respect** the Content rules

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IMPORTANT NOTE: this Milestone 2 feeds on Milestone 1 - Understanding.

Table of contents

How to read this document

Growing consensus

The *Growing consensus* box is a summary of a section of this report.

Attention

The *Attention* box points out some important things to consider.

Alternatives

The *Alternatives* box enumerates possible solutions to consider.

Reasoning

The *Reasoning* box presents arguments about possible choices.

Information

The *Information* box tells you how stuff works.

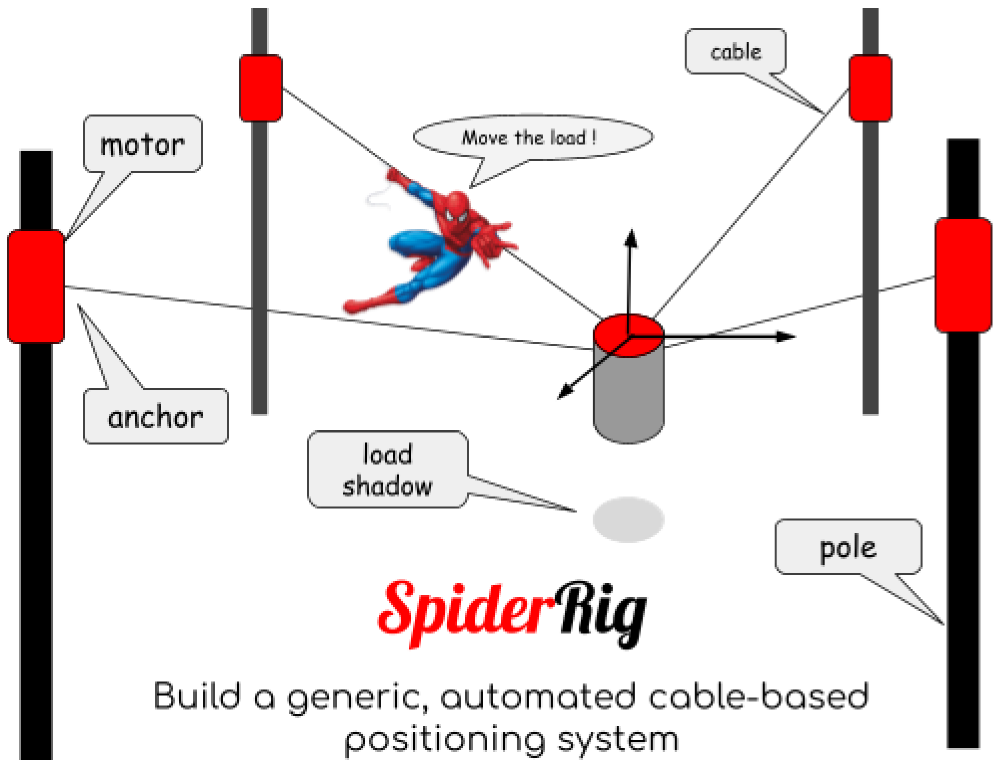
Project Description

Design and prototype a **planar cable parallel robot**, able to move a load in 3D space with **constant and small speed, close to static balance**, and **with real time feedback from the actual position of the end effector**.

Project web page.

Main components and vocabulary

TASK: complete the picture and add list of important terms



- **Motor**: electromechanical actuator used to ...
- **Cable parallel robot:**
- **Anchor**: A point of attachment of a cables
- **Pole**: A rigid, telescopic pole on which the motors are mounted.
- **Load**:
- **End effector**:
- **Motor driver**: electronic device used to control the *Motor*
- **Microcontroller**: an electronic board used to communicate with the *Motor driver*,
- **Gimbal**: an electromechanical assembly used to control orientation two or three axis of rotation.
- **Moving Attachment Points**: passive, freely rotating cable connectors attached on the end effector.

Our Values in Action

This project is developed in an *open* and *transparent* way by SENSORICA, an *open value network*. What we mean by open is that anyone in the world can contribute. Our commitment to transparency means that everything is documented and made public as the project develops and is delivered. As an open value network, SENSORICA creates opportunities for anyone in the world to contribute, track their work, and receive compensation for their efforts.

From the beginning of this project and throughout the first milestone, we launched an outreach campaign to raise public awareness and attract participation. We created a list of different communities that we thought might be interested in working on the project, contacted members of these communities directly, and engaged in a social media campaign.

Insert NRP-CAS data from Milestone 1

Insert stats from our outreach campaign

Design considerations

The goal of the first milestone is to perform a comprehensive review of all the required components, and to choose the best features that match the project goals.

- The first stage, '*General Considerations'* is a high-level design effort to take into consideration key characteristics. Please note that these characteristics maintain important relations and they cannot be considered on an individual basis.
- The second stage is to aggregate the different designs and design ideas.
- The third stage is to make an informed choice of features to be blended into the design.

General, system considerations

Ecosystem A reflection about standards to be used, based on a map of the ecosystem this product will be part of. The goal is interoperability.	**Power sources**: The system needs to be compatible with a 110V AC power source. In case of power outage the system needs to be able to recover without major problems. **User experiences and interfaces**: Needs to have a very intuitive, user friendly, simple user interface.
Lifecycle A reflection about how this product will be used and who it will end its life. Is it modular and used in conjunction with other things (see System)? Is it a "perpetual product" (i.e. the user is able repair and to update/upgrade it) and if so, how easy it is to be updated/upgraded? Will it be possible to recycle parts of the product to be used in other applications once the product becomes obsolete? Is it recyclable? Is this product meant to be shared by a group of individuals during its lifetime?	**Lifetime**: The system should be designed to be maintenance free for at least 1 year. **Evolution**: In its first implementation, the system will be an alpha product, a prototype that needs to rapidly evolve to the beta state, and on a longer term evolve towards a stable system that can be constantly and efficiently used in different domains of applications. Designed to be modular, replacing a major material components with another equivalent component without affecting the rest of the system. Chose open source software that allows the same flexibility for adaptation and improvements. Updates or improvements will be implementable by people with low (technician-level) technical skills, using common equipment and tools. **Fabrication**: Built from readily available components, most of them open source. Assembly will be easy, requiring low (technician-level) technical skills. **Regular use**: Used by individuals with no technical skills. Easily mounted and dismounted, and packaged for transportation using no technical skills and commun tools. The system will be highly transportable, able to sustain rugged transportation conditions. **Regular maintenance**: No special tooling required to assemble and maintain the system. A detailed assembly and maintenance manual. **Repairs:** Can be serviced by a local person with minimal technical skills, by following a short list of instructions. Modular system, every module easily accessible and replaceable. All cable connections are designed with low risk for injury or damage to the rest of the system. Connectors must be color coded and unidirectional. Every module needs to be changeable without having to touch the other modules. No special tooling should be required to replace a module. Detailed system repair manual.
Business model A reflection about how the product is generating value for the community that designs and supports it. Is the value capturing mechanism based on	**Service-based commercial use and personal use** Service-based commercial use presupposes responsibilities between service provider and client. Safe to use, reliable and efficient. Serviceable by users with very low technical skills in the field, if problems occur, by rapidly replacing the faulty module

service? Is this a product that is owned or rented? Is the product serviced on site or remotely? Is this product labeled as a sustainable product (local, ethical, environmentally friendly).	only using instructions in the repair manual or other types of online resources. The context of service-based application is a rapidly evolving. The system is able to rapidly adapt to new and specific service demands and conditions. Easily upgradable by people with low technical skills, following a set of instructions provided by the community/ network of innovators, available manuals and other types of available online sources of information.
Manufacturing A reflection about supply chain and fabrication. What are the optical supply chain and parts in order to reduce cost and environmental impact. What the best fabrication technology/method? How important is quality?	This will be an alpha version, a one of a kind prototype, designed to rapidly evolve towards a beta version. In its first iteration the system will not be designed for mass production and distribution. **Suppliers**: Parts that can be sourced locally, reduced lead time in case of problems, allow rapid parts exchanges and repairs. Choose brands that have a continuity for sustained interoperability. If a module is upgraded it maintains its interoperability the remaining modules of the system. Parts will be chosen for their availability and technical support by the manufacturer, preferably open source for their flexibility, modularity, intercompatibility, low cost, level of adoption and constant improvement. **Assembly**: Plug and play modular architecture. The electronic connectors need to be marked, color coded, and one sided. Every module needs to be changeable without interfering with the other modules. No special tooling required to assemble the system. Make sure that the fixtures and support structures have some degree of flexibility, in order to allow replacement of these modules with other versions that might be slightly different. Assembly, upgrades and repairs system should be possible in an environment that offers a minimal level or rapid prototyping equipment and common technical skills (for example a fablab or makerspace).
System A reflection about how the thing will be put together.	This system will be modular. In Milestone 1 we have identified it's main material components: positioning sensors, electrical motors, motor controllers, power supply(s), motor drivers, cables, motors fixtures. It may have also motor gear boxes, polleys, counterweights. Most of these components need to be replaceable with other equivalent components to preserve the adaptability of the system. On the software side, the system will be composed of firmware (to run the motors), 3D path generation and conditioning module, a GUI interfacing with all the previous modules. The software must be modular and well-documented to allow rapid improvements. High software and electronic hardware compatibility is required to reduce the costs of innovation and adaptation.

Environment A reflection the environment in which the product will evolve	In the first application the system will be used indoors, protected from natural elements. Contains safety features to prevent harm to itself and to users, as it will be used in an environment shared with people with limited technical knowledge about the system. Designed for easy transportation and storage under rugged conditions, resist moderate shocks and vibrations, as well as temperatures between -10C to +40C.
User effects A reflection about how the product is handled by the user and how the user can affect the integrity of the product	The typical user has no technical skills. The system should be plug and play, requiring very limited intervention for installation, calibration and use. Possible problems: ● Cables might snap and cause damage or injuries. ● Motors might jam during operation. ● Cables might interfere with objects within the working space. ● Load motion might go out of control and cause damage or injuries. ● Electronic material might be dropped during transportation, assembly and disassembly.

Other desired design characteristics

- **Shareable (the sharing economy)**: The system is designed to be safely borrowed/lended or rented. It should not need extensive training to operate. It will also be safe to operate limiting the usage liability. It can have software or hardware based geolocalization features, and/or a user-login and use parameters ledger. The system can also be provided with hardware for abuse recording (accelerometers for example).
- **Modular (perpetual products and customizable)**: Already covered above
- **Interoperable (use widely adopted standards)**: The system will be easily customizable for other applications. Thus, it will be designed to be able to interface with other existing software and hardware used in that same context. Thus, a very good API must be provided.
- **Socializable (offer value through social interactions and communities):** The GUI must allow sharing of important parameters of use through different commonly used means for messaging. It must also allow export of products of its use into highly portable and Shareable formats.
- **Sustainable**: Prioritize low power consumption electronics, readily available materials, components that have been produced under ethical and environmentally safe conditions.

See Sensorica's product design philosophy doc.

We should always think larger than the project. There are different dimensions that we can identify.

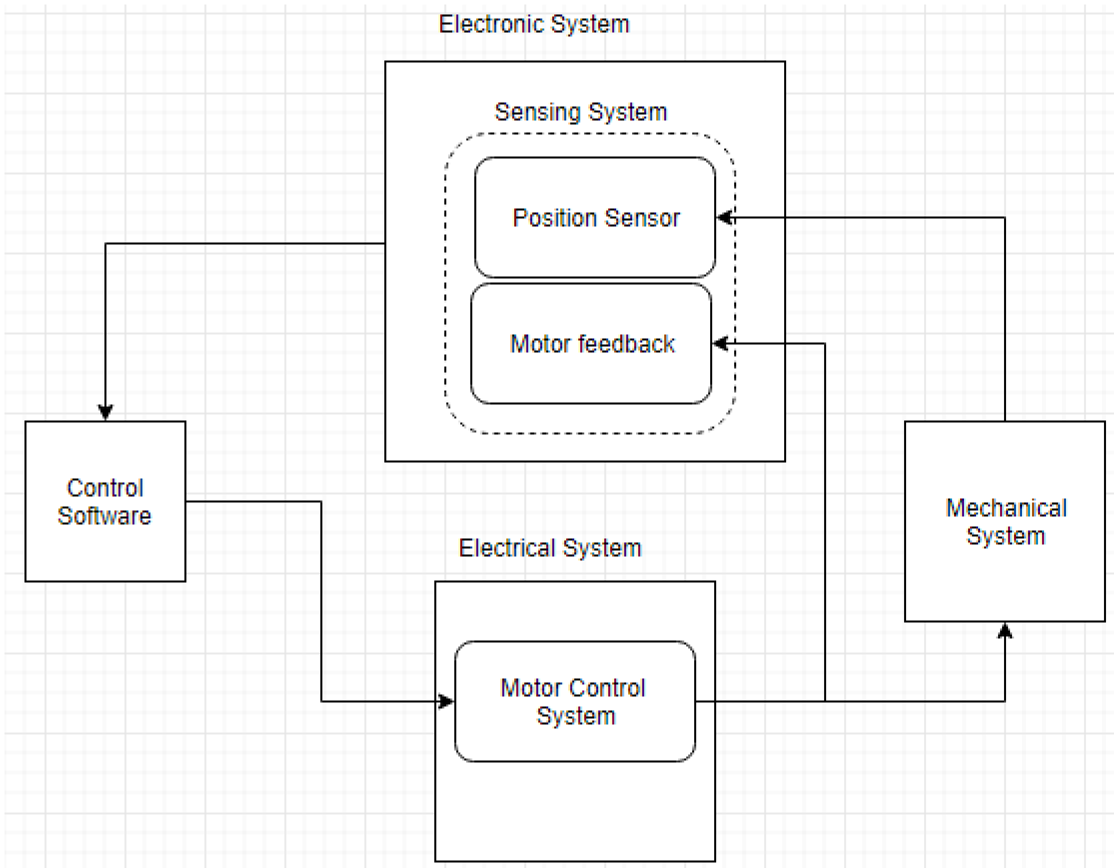
For Sensorica

- **Synergy with other SENSORICA projects**: Smart soccer, eCommunity gardening and GreenSense
- **Spinoffs (modules that can take a life of their own)**: FarmBot
- **Parallel opportunities**: eco2fest and Verdun
- **Network building - cohesion, activity level, energy…** : Attract highly qualified skills to the Sensorica network, expose Sensorica's peer production model.
- **Network of network consolidation - build bridges with other networks**: FarmBot, Hangprinter, cable robots ecosystems, automation ecosystem

General technical requirements

- 4 to 8 cables
- 3 degrees of freedom (xyz displacements),
- **low speed** of operation, constant speed motion (almost steady state or close to equilibrium),
- <2cm precision,
- good 3D path **repeatability**,
- carry 2 to 5 Kg loads,
- workspace max volume 10m^3, with **variable geometry** (can take any shape within this cube),
- low cost,
- versatile and highly adaptable to various geometries (i.e. variable anchor position in 3d space),
- large work space compared with the volume enclosed by anchors,
- simple user experience and interface.

The system will have 4 main components; Control Software, Electronics System, Electrical System, and Mechanical system. Each system will be discussed in a separate section except the Control Software, which will be mentioned as needed, since this project is focusing on the hardware implementation.



Risk analysis

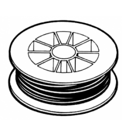
The risk analysis is instrumental in prioritizing analysis and design efforts. By quantifying the risk associated with uncertain problem areas, concerns or the effects of alternative designs, we are better able to focus on the right decisions at the right time. We use this table to resolve the higher-risk items as early as possible in the project.

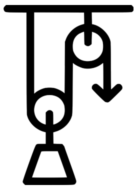
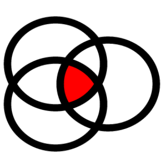
Design Risk	**Response**	**prob**	**mag**	**Risk**
Rotation of the end effector	Crossed-cable configuration	0.5	8	4
Instability of end effector (oscillations, bouncing, etc.)	Linearity Simplicity Position sensor precision Minimum latency	0.8	10	8

	Alejandro: *CDPR requires more effort in finding the stability than precision (I wouldn't use steppers in a CDPR)*			
Cable overtension - stretching and breaking of cables				
Structure or workspace configuration				

Key design decisions

Some key design decisions may be understood as such without necessarily having a direct, immediately understood connection with specific risks. As such, the following table permits some sequencing and prioritization of work that is driven by factors other that considerations of risk. For instance, some design decisions have greater or lesser downstream impacts - being associated to more or less design dependencies. Together with the risk analysis, this decision table facilitates strategic action planning that minimizes risk and re-work.

	Deliberation	Impact/ dependencies
Number of cables		
Cable winding (winch, spool or counter weight)  	Spools are used by the [Hangprinter](#) project. This solution is simple. In the Hangprinter case a correction for the spool is used in the kinetics algorithm to compensate and recover the precision loss. But we don't need high precision. Industrial cable robots use winches. Increases costs. Haven't seen a cable robot using counter weights, but since we only need slow accelerations and speeds, this solution seems to be viable. Limits acceleration and speed, more complex than a simple spool.	

		
Cable configuration (how are cable passed around: single string, double string, crossed cables to control rotation?)		
Geometry variable!		
End effector geometry And cable attachment points		
Gearbox 	Reduces torque at the motor → smaller motors can be used. Works for our low speed application. Better precision.	
Motor location (on the end effector or at the anchor points)		
...		
...		
	Enter reason for the final choice here...	

Action planning

Task	Assigned	Due
Produce life-size model of load assembly (size, shape, attachment, weight) - since it will not be practical to test and stabilize the design using the specific load envisioned for initial usage.		

Software design considerations

IMPORTANT NOTE: the Sponsor is in charge of software development, which includes 3D path generation and UI. **We only need to focus on the firmware**.

Firmware hardware compatibility	Hardware compatibility	Examples of use	Score
Merlin	Used with Arduino.	Designed for 3D printing. Has been adapted by Hangprinter.	
Machinekit	Used with board computers such as RaspberryPi, Beaglebone, etc.	Used by Arcus-3D-C1 project	
Klipper	Used in 3D printing		
Skycam	Used with Arduino. Designed for cable robots		
...			

	Enter reason for the final choice here...

From Alejandro:

- CDPR requires more effort in finding the stability than precision (I wouldn't use steppers in a CDPR)
- Dynamics is important in the control algorithm, even for low speeds (due to the center of mass).
- CDPR is an elastic parallel robot. Because you are looking for 2cm accuracy maybe this is not important if the robot is not huge.
- Zero-positioning and calibration is complicated.
- variations in the load of the end-effector have important effects in actuation control.

Electronics design considerations

Sensors

- Hive Tracker (real time position and orientation)

Motors + encoders & controllers

- Servo motors type: actual motor to be determined
- oDrive motor driver

System brain

Single board computer running a version of Linux real time/

Wire management: Need to be careful with wire management, cable distance for digital communication

Parameters to be sensed

The main target of the sensing system is to find the load position in 3D space. It can be divided into two subsystems; motor feedback, and load position. In order to achieve this goal different sensors are required. For motor feedback, we need to measure motor speed and direction. For load position, the sensed parameter will differ based on the sensing technique. If UWB technique is used, then appropriate receivers and transmitters are required. If a mechanical technique is used, then angle and distance sensors are required.

Sensors to be used

One alternative to determine load position is the POZYX kit, or a combination of angle and distance sensors (see milestone 1). POZYX uses UWB signals to detect the actual position within its transmission range. The angle & distance sensors technique is based on measuring the cable angle with the anchor points and the cable length between the anchor point and the moving load. Triangulation is then used to calculate the actual position.

Motor feedback subsystem is used to determine the motor actual position and speed. Although the positioning subsystem information can be used to control motor behaviour (i.e. speed, and direction), but the feedback system will be important in the calibration phase when system starts up.
data from the position sensor can be fused with data from the motor encoder to achieve better accuracy (Note: will be affected by elasticity of cables)

Characteristics:

Another alternative for indoor applications is HiveTracker

Characteristics:

Design consideration:

For the selection of motors and cables some behaviour aspects of the CDPR (Cable-driven Parallel Robots) should be taken into account:

- High torques is more important than speed for the following reasons:
  - High acceleration is not required in the first embodiment of the system.
  - Suspended cable robots requires a heavy payload to maintain tensions and they have low stiffness (mainly in z-axis) so it is more important to have low speeds.
  - The motor has to be able to provide smooth movement (an instantaneous high acceleration means vibration in the end-effector)
- Measuring of motor torque is important (e.g. by measuring the current). The oDrive motor controller has a torque mode. Mechaduinos have it too.
- Stability is more important than precision
- Dynamics is important in the control algorithm, even for low speeds (due to the center of mass)

In the future, if high speed is required, we need to consider the following:
- a more complex control algorithm or higher degree of redundancy (= degrees of actuation - degrees of freedom (r = m - n))
- The motor encoder system should have a high sampling rate to measure fast movements of the motor.

Mechanical design considerations

Design consideration:
- A weight/ballast can be added to the end effector to increase stability. A software analysis can be used to guide the user on where and how much mass can be put in the end-effector
- For auto calibration, we need to identify an initial (i.e. zero) position. This can be achieved by using absolute encoders
- The workspace dimensions is variable, but it should fit into a 10m^3 cube.
- Cables should have minimal deformation and bending. Bendings and contacts can decrease cables' lifetime.

Harvested from discussions:

Alejandro:

I personally like to work with brushed or brushless DC motors with a good gear system that provides higher torque and lower speed.
I think that for the selection of motors some behaviour aspects of the CDPR (Cable-driven Parallel Robots) should be taken into account:
- It is more important high torques than speed.
- It is important the measuring of the torque of the motor (by reading the current, for example).
- The motor has to able to provide smooth movement (an instantaneous high acceleration means vibration in the end-effector)
- High speed in a CDPR that has not any spine (a rigid link to maintain positions) requires more complex control algorithm or higher degree of redundancy (= degrees of actuation - degrees of freedom (r = m - n))
- The encoder system of the motor should has high sample rate to measure fast movements of the motor.

Suspended cable robots requires a heavy payload to maintain tensions and they have low stiffness (only in z-axis) so it is more important to have low speeds. Fully constraint

CDPR have higher stiffness so they can achieve higher speeds. However, more torque is needed to compensate tensions that comes from the lower part.
Motors and amplifiers should be chosen looking at the needed torque and speed. And those values are obtained after analyzing the structure and dimensions of the robot.
I agree with the motors you have selected (brushless) and I also like raspberry or odroid (as you mentioned)

Aref:

4 cables is optimal. More cables make the system more complex to control and requires clear justifications.
Polymeric cables are preferred over steel cables. With steel cables more weight is added and will get high catenary effect. On the other hand, with nylon (or similar) cables, you have more deformation, but deformation is preferable to catenary. It should be noted that polymeric cables are also subject to length changes based on their temperature.