Robustness data of a large dimension cable-driven parallel robot in a 3D-printing task

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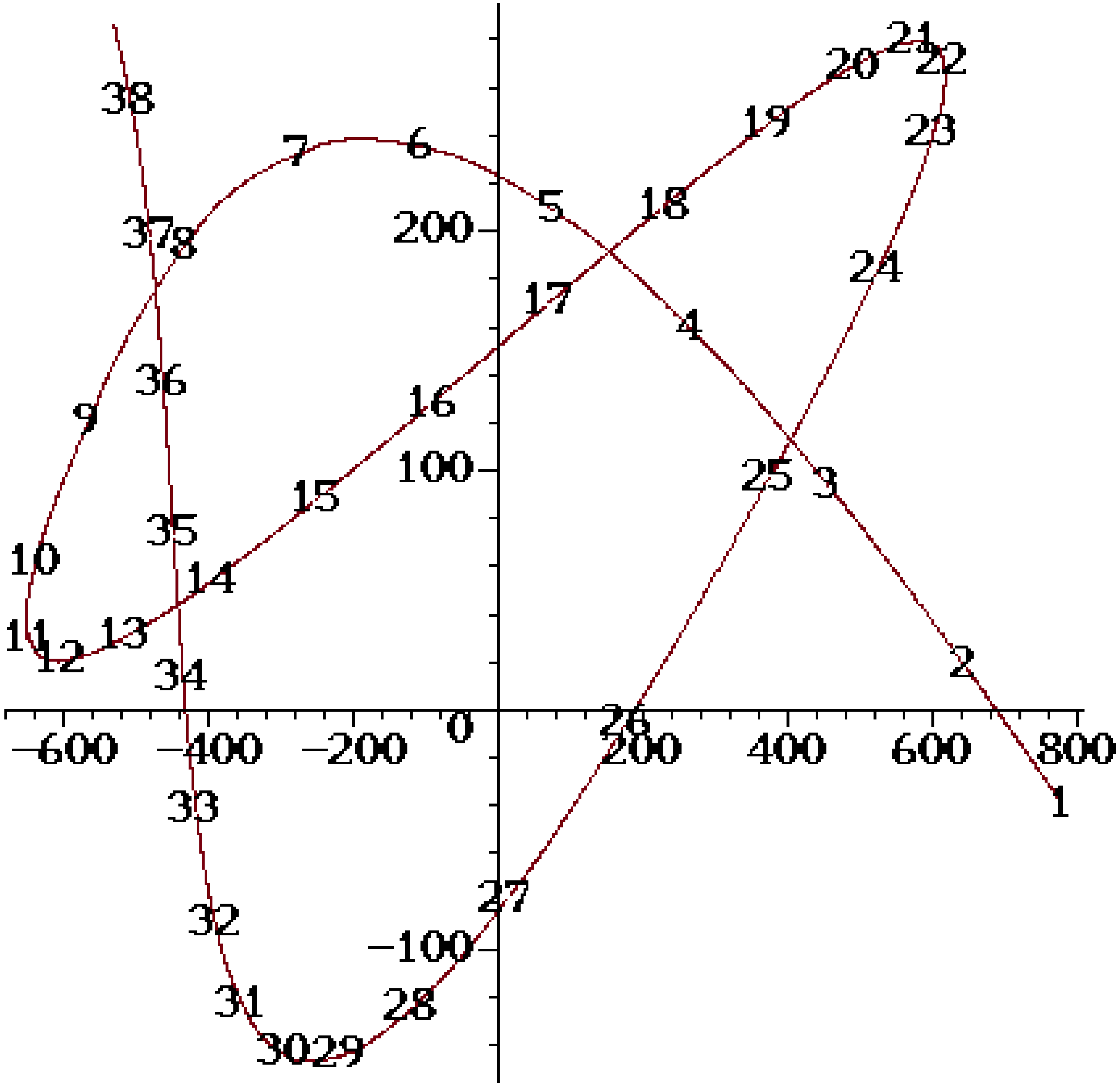
The project

Artistic exhibition purpose:

- spreading layers of a powder made of glass micro-beads over a given trajectory given by the artist A-V. Gasc
- orientations are not needed
- no glue in the powder $\Rightarrow$ the structure evolves after each new layer

- large workspace: $20.4 \times 9 \times 3.8$ meters, bad ratio length/height (5.3) $\Rightarrow$ cables are close to the horizontal
- few elements around the workspace: 40×40 cm pillars every 6 meters

- trajectory: 40 meters at a mean speed of 3.5 cm/s
- 20 kg of powder/layer



Context

- exhibition has to be run from June 22 to August 31, 2019, 5 days a week between 10am and 8pm
- exhibition place located 900 km away from Sophia-Antipolis
- exhibition has to be run by a student in architecture

The robot

4-cables CDPR, 3mm Dyneema cable, load: 40-60 kg, winch with up to 200m of cable, output point: pinhole in Delrin (simplify the kinematics)

Drum

- 3 lidars (1 vertical, 2 horizontal, range: 10m, sampling rate 10Hz, cost 100 euros)
- accelerometer/gyrometer
- light sensor: to detect lack of powder
- servo-vane at the bottom
- fit-PC
- wifi connection

Computers

- one master computer (Linux)
- one fit-PC on the drum (Linux)
- connected with wifi and a message passing scheme
- Phidgets and dedicated motor controller
- measurements and motor control sampling rate: 10 ms (accelerometer: 24 ms)
- file logs both on the master computer and fit-PC: record sensor data and robot internal state every 2 seconds

Control

Initially

- ideal cable are assumed
- high level: cartesian speed control
- low-level: cartesian speed transformed into cable velocities
- require to solve the forward kinematics with measurement of the cable lengths
- cable length estimation:
  - based on winch rotation measurement with a layer model
  - detection of small aluminium foils at known cable length

Control

Initial tests

- accuracy with aluminium foils was good: positioning error less than 2.5 cm on x, y, less than 1cm on z, independent of the load (measured by theodolite, static measure)
- BUT
- the glue on the foil was not able to sustain a large number of trajectories
- without the foils accuracy starts diverging over a whole trajectory because of poor estimation of cable lengths

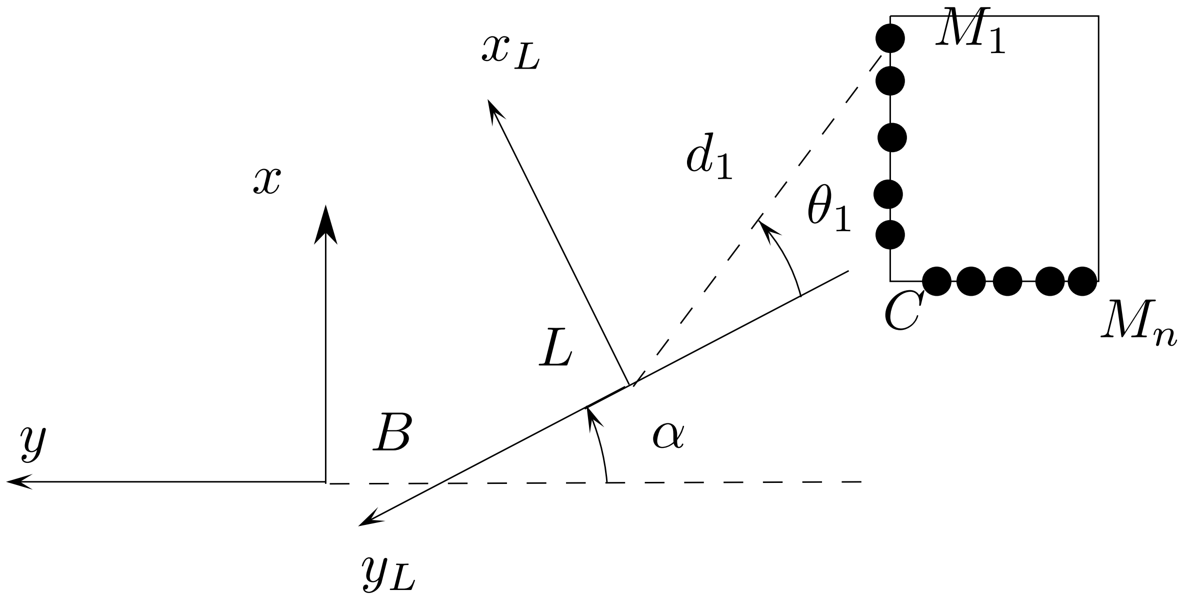
$$\Downarrow$$

control strategy change with the use of lidars

Control with lidars

Idea: measure directly the drum pose with lidars

- a vertical lidar for measuring the drum z by detection of the planar floor: accuracy better than 1mm
- 2 horizontal lidars for measuring x, y by pillar detection



Control with lidars

Problems

- lidars have a relatively low sampling frequency (10Hz)
  - between lidars data pose is measured by using the winch rotation measurements
  - as soon as a valid lidar pose is obtained current cable length is updated (together with drum radius estimation)
- pillar not always detected:
  - pose is estimated by fusing the lidar z estimation and winch rotation measurements
- good accuracy: about 1cm for x, y, less than 0.5cm for z (measured by theodolite, static case)

Experiment

During the exhibition

- total use time: 174h
- mean daily use: 4h 15mn
- total travel distance: 4757m
- maximal cable tension: 1263 N (not measured but estimated from the static analysis)
- 76 printed layers, 1.5 tons of powder
- 2 To of data
- 25 000 lines of code

Experiment

Drum rotation

- around the z axis:
  - estimation with the pillar detection: very good accuracy
  - estimation with the gyrometer: diverge over time
  - worst case rotation: $\pm$ 5 degrees
- around the x, y axis: with the gyrometer with good accuracy
  - rotation up to $\pm$ 7 degrees (unavoidable because of sudden changes in travel direction)

Problems

- one cable breakdown: the aluminium foils have not been removed and have created a very abrasive ball at the winch output point. Otherwise very low cable abrasion (justify the pinhole output point)
- one winch partial breakdown (winches are 4×4 wheels winches, 50 euros a piece)
- 1 servo-vane breakdown

Major problem (1)

- low weight of the cable not under tension
- when unwinding such a cable it is stuck at the output point because of friction
- winch unwinding may create a cable loop at the winch level that invert the relation cable unwinding/motor rotation direction
- $\Rightarrow$ while we believe that the cable unwind it is winded $\Rightarrow$ the drum goes up instead of going down

Detection: through the z lidar

Solution: small counterweight on the cable close to the drum to create cable tension

Major Problem (2)

- cable slackness cannot be avoided: most of the time only 3 cables are under tension (and episodically only 2)
- but the triplet of cables under tension changes over the trajectory (configuration change) $\Rightarrow$ positioning error until the slack cable becomes under tension
- error estimation during configuration changes (with the accelerometer): up to 5 cm

Evolution

A new exhibition should have taken place during ICRA 2020 that has been canceled because of the Covid

- severe workspace constraint: 5 $\times$ 5 meters, same winches

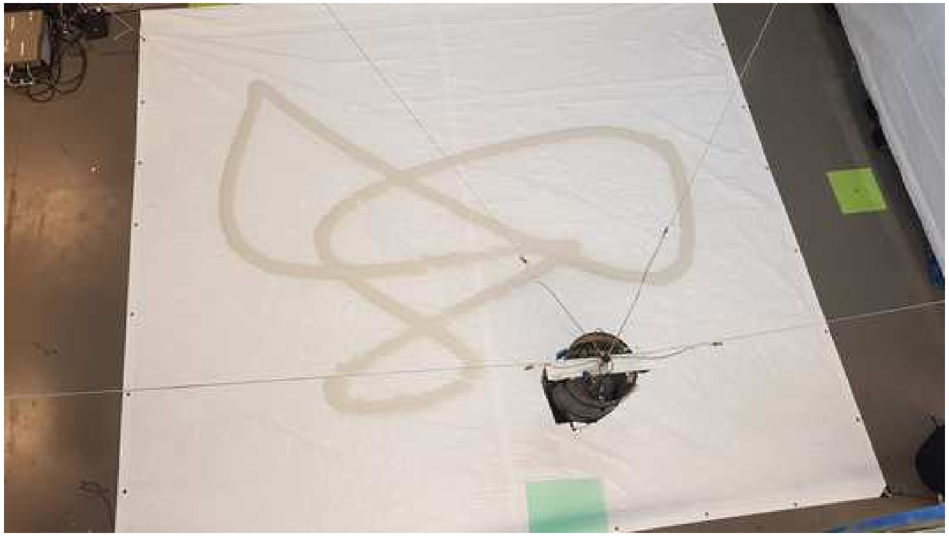
Evolution

- using flip-flop pulleys: not convincing
- inverse and forward kinematics based on pulleys and sagging cables (no elasticity)
- accelerometers located at fixed position on the cables
  - provide cable angles
  - allows to reduce slackness (accuracy improved to $\pm$ 2cm)
- 3 reference walls: detected by the horizontal lidars, allows to get the x, y drum coordinates at all time: very good accuracy (better than 1cm)
- increased lidars sampling frequency (10Hz $\rightarrow$ 20Hz)
- tested for 90 hours

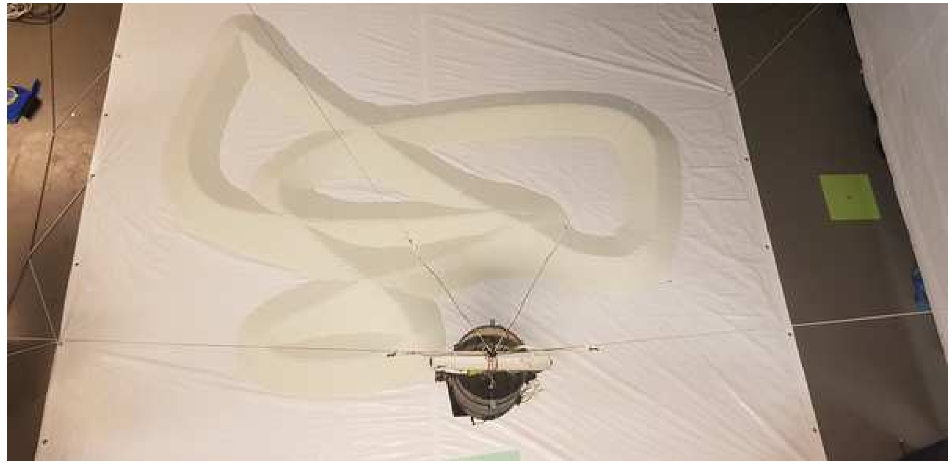
Conclusion

- realistic long time tests, without any maintenance
- even with low cost hardware CDPR are able to perform quite well (cost $\approx$ 3000 euros) in industrial conditions
- accuracy was not a strong constraint for this test: however it is shown that lidars is an interesting on-board option for determining the pose which makes control easier
- the influence of cable slackness has been strongly decreased

Some fun

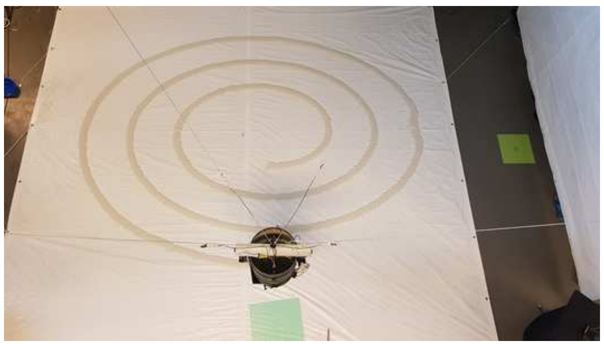


layer 5

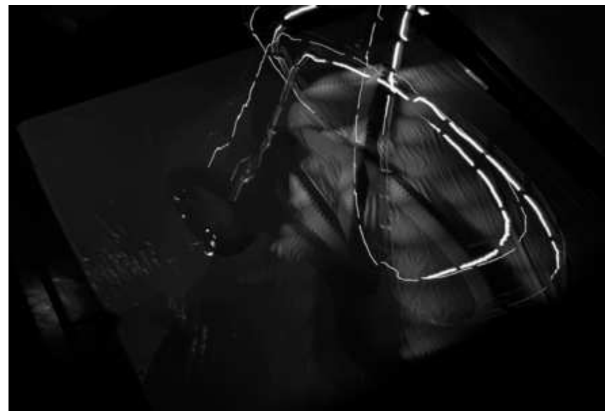


layer 38

logo



Archimede spiral



led at night