On the Design of a Fast Parallel Robot based on its Dynamic Model

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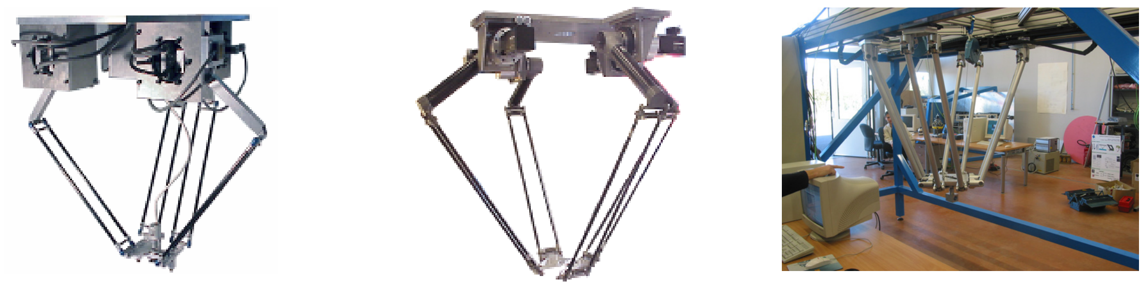
1 Motivation, Problem Statement, Related Work

Most pick-and-place applications involved four-degree-of-freedom robots; indeed, packaging, picking, packing and palletizing tasks required three translations and one rotation around a vertical axis and such motions, named Schoenflies motions [1] or Scara motions, have to be realized in the shortest possible cycle time: the need for 4-dof, Scara-like, robot mechanisms able to reach high speed (typically more than 4 m/s) and high acceleration (typically more than 100 m/s^2) come directly from such applications. To date, two families of mechanism architectures have been intensively considered, studied, and used in numerous plants: the simple and efficient **R**-**R**-**R**-**P** serial chain which is the base of all Scara robots, and the parallel Delta robot [2] which was specifically developed by Clavel at EPFL at the end of 80s to tackle pick-and-place tasks. In order to reach high accelerations, this machine was designed with all actuators fixed on its base which minimizes moving parts masses. However, the rotational motion of this robot is obtained using a central **R**-U-P-U-R chain (R: Revolute, U: Universal, P: Prismatic, bold representing the actuated joint) which could suffer from a lack of stiffness at workspace boundaries. In addition, this telescopic arm has a short service life.
Apart from those two famous robot categories, other lower mobility parallel mechanisms able to realize Scara motions have been developed in the recent years. For example, Angeles [3] proposed a four-dof parallel mechanism. In addition, EPFL developed Kanuk and Manta robots [4], and the machine tool HITA STT which has been modified to pick-and place manipulator [5].
However, it is worth noting that these innovative robots have been designed by mostly (only?) resorting to *kinematics* considerations, such as optimizing their architecture with respect to kinematic manipulability or "isotropy". Obviously, such considerations are of tremendous importance and no one can ignore them, but we would like in this paper to show, on a practical example, how *dynamics* can affect the *design* of a fast parallel robot in the view of optimizing its behaviour for pick-and-place operations.

2 Technical Approach

The first step of our approach was to create a "evolution" of a concept we came up with in the last 5 years as a way to obtain high speed PKM, the concept of "articulated" travelling plates, of which already three implementations are running: H4 [6], I4L and I4R [7]).



(a) H4 (b) I4R (c) I4L

Figure 1. Three different implementations of the « articulated » travelling plate concept.

The motivation to improve both H4 and I4 has indeed two aspects: one is related to kinematics (namely, the way to properly handle this very specific singular positions that we call "internal" singularities and that differs from either "serial type" singularity or "parallel type" singularity) and the other is related to technology (namely, the choice of revolute joints on the travelling plate instead of prismatic joints because of constraints due to high speed and acceleration). This first step gave the PAR4 prototype, where the travelling plate is based on a articulated parallelogram.
The second step was to derive a detailed dynamic model of this mechanism and to do so, we resorted to a modified Newton-Euler technique and a few, extremely realistic, simplifying assumptions. This step has been followed by a third one: we have identified this dynamic model and all that was verified by cross-validation.

With those results in hand we, as a fourth step, had been able to set up a realistic simulation model and thus we have been able to evaluate the torque required for any motions, including obviously classical pick-and-place motions. Analysing such simulation results shown that, for real pick-and-place motions, the torque demands on each motor were actually drastically different, leading to a non optimal use of actuators, and limiting the overall performances (two motors reaching their limits far before the others).
The last step has been to search for a modification of the architecture able to radically homogenise the dynamic behaviour as far as the demand for motor torque is concerned.

3 Results

Results of this work can be summarized as follows:
- Results obtained in our "incremental" research process: efficient modelling of complex parallel robot dynamics[1]; identification of the complete dynamic model (mass, inertia, friction) of this parallel mechanism[2]; analysis of this model by means of simulation leading to a detailed understanding of the robot behaviour;
- Result obtained as a direct output of this search: a new, improved, more "dynamically balanced", parallel mechanism. Starting with the analysis described a few lines above, we have been able to propose a modification of the robot kinematic (precisely: a change in the travelling plate) that leads to a (much) better "load share" among motors during a pick-and-place operation: for the same motion the maximum torque was **330 N.m** with the first design, and only **230 N.m** with the improved design proposed after the analysis of the dynamic model. It is worth noting that the change concerns only a very small part of the robot (weighting only a few grams, indeed) but this "*kinematic*" change had a remarkable effect on the dynamic model and behaviour: we did not change the weight or inertia of parts, but made a "small" change in the kinematic design that had an impressive effect.

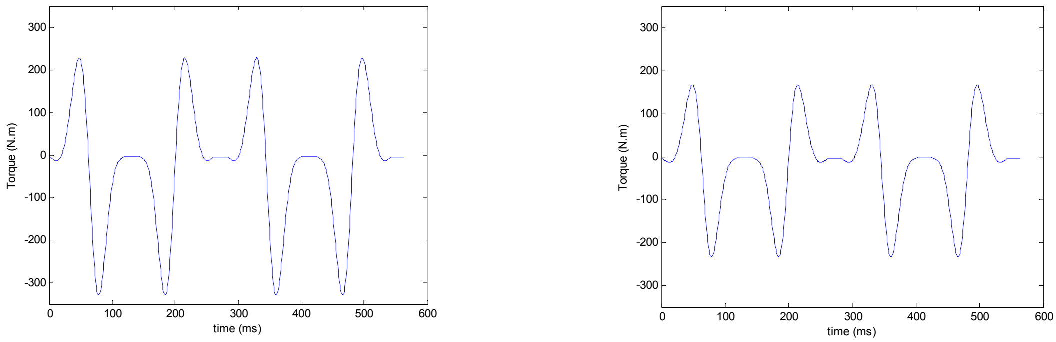


Figure 2. Evolution of motor torque during a pick-and-place operation (acceleration: 15g): before the design improvement (left plot) and after the design improvement (right plot).

4 Experiments

Experiments have been conducted for two purposes:
- Evaluation of the dynamic model parameters; in Figure 3, the plots show that the cross-validation confirms the accuracy of the identification.
- Verification of the robot capabilities for pick-and-place; in Figure 4, the left plot depicts the classical "Adept cycle" and the right plots show the tracking accuracy during a cycle (acceleration:10g; velocity: 2.5m/).

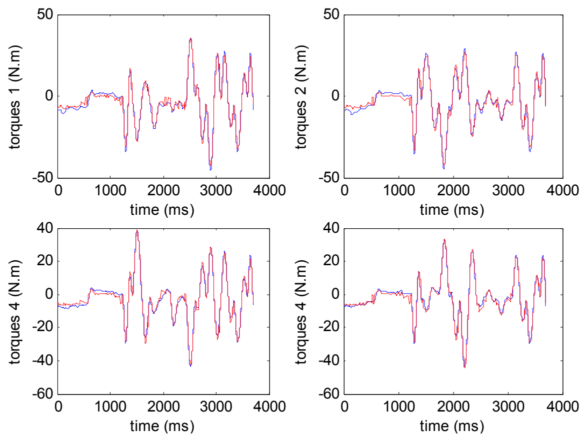


Figure 3. Cross-validation for assessing the dynamic parameters identification.

[1] The model will be described in details in the final paper.
[2] The identification process will be described and the analysis of plots and curves will show the accuracy of the results.

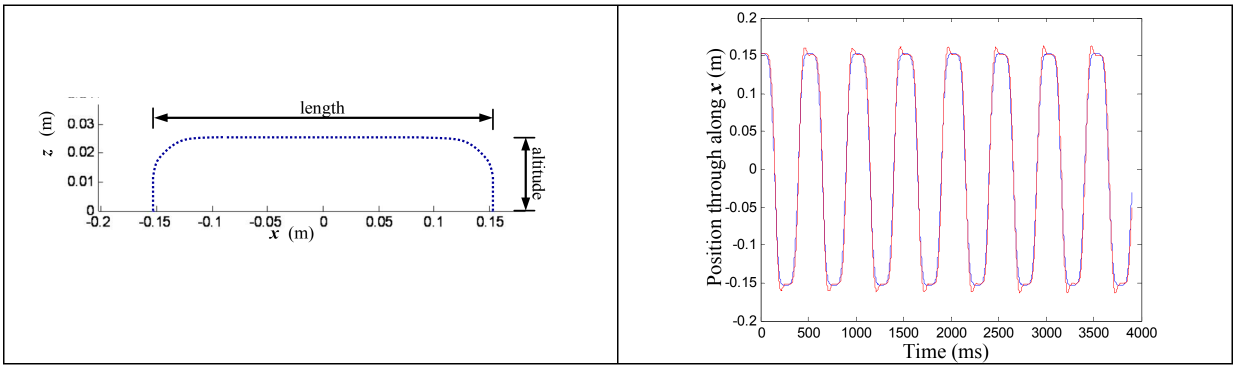
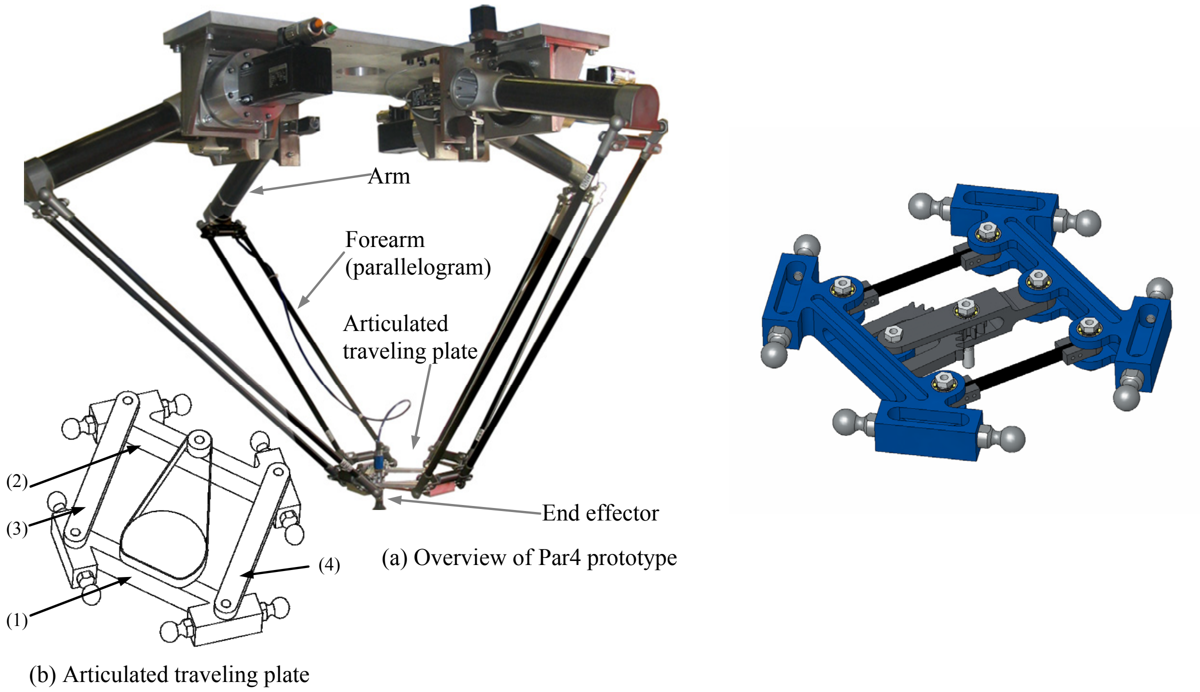


Figure 4. Experimental verification of the robot efficiency for pick-and-place

5 Experimental Snapshots



(a) The original PAR4 (b) The modified design

Figure 5. Two views of Par4: the original design and the modified one.

6 References

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