Towards Non-Hexapod Mechanisms for High Performance Parallel Machines.

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Abstract

The so-called "Hexapods" are extremely popular in the research community, but much less successful in practical industrial uses so far. This paper discusses some reasons that could explain this difference. Alternate solutions, based either on simpler mechanisms or on hybrid mechanisms, are described or recalled. An emphasis is made on some new hybrid mechanisms whose important features are motors rigidly fixed on the base and legs with constant length.

1 Introduction

From the first ideas of parallel mechanisms proposed by Gough [1] or Stewart [2], a lot of interesting mechanical devices or design methods have been extensively studied. Until the mid 90's, most of those researches have been done by the robotic community, and it is clear today that the biggest efforts have been dedicated to 6-degree-of-freedom (*dof*) machines which are now well known (see [8] and [5] for an exhaustive enumeration, and [4] for a complete scientific background) or 3-*dof* machines (see [9] and [10] for good examples of such devices).
More recently, the machine-tool industry discovered the potential advantages of parallel mechanisms and major machine-tool companies are evaluating their own parallel prototype of machine. Clearly, the requirements of machine-tool industry are much higher than those of robotic industry in terms of accuracy, resolution, stiffness: a good parallel machine-tool would be a high performance piece of equipment!It is worth noting that almost all solutions tested nowadays by the machine-tool industry are based on the so-called "Hexapod" solution, that is to say: 6 *U-P-S* chains arranged in parallel (*U-P-S*: Universal-Prismatic-Spherical joints) between a base and a nacelle carrying the spindle, and the *P*-joint being actuated.From the basic hexapod design (followed for instance by Fanuc) where all joints lie in two plane, designers have tested various arrangements:

- ✓ Crossing-leg Hexapod (e.g. Variax);
- ✓ Non-planar base (e.g. Ingersoll);
- ✓ Non planar base and nacelle (e.g. Mikromat and Hexact).

So it seems that many of the possible arrangements have been practically investigated, independently by academic institutions and industrial research centers with, to date, very few "real" success, that is "commercial" success…

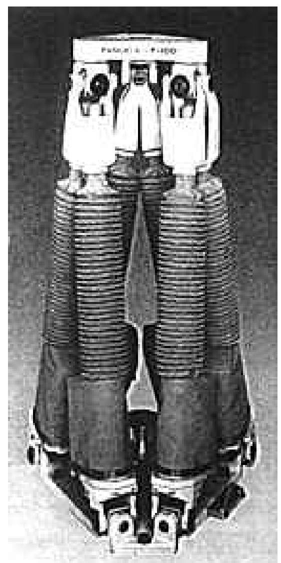

Figure 1. F100i (Fanuc)

It may be interesting to take few moments to think about that fact, and to try to point out some of the reasons behind that. This papers will first discuss some of the possible reasons; then it will present or recall existing solutions to this problem. Among the solutions, one will be more deeply discussed: it could be summarize in one key sentence: "if it's too hard to make it parallel, make it simple". Finally an example of preliminary work towards this direction will be presented.

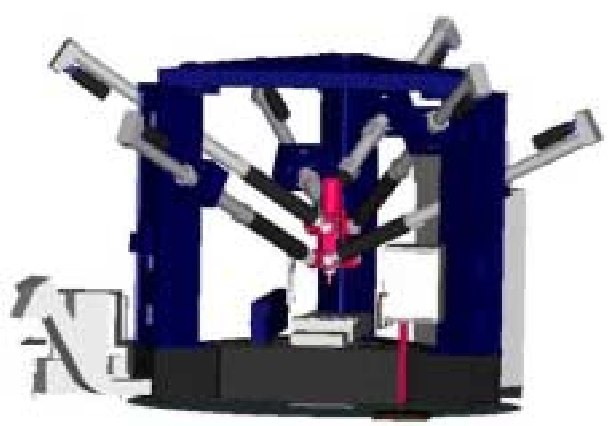

Figure 2. 6X (Mikromat)

2 Some limiting factors for Hexapods

Among the limiting factors for the practical use of Hexapods in the machine-tool industry, we can distinguish several cases:

- ✓ **Some factors are in fact common to most parallel mechanisms**, such as, for instance, a poor ratio between the workspace volume and the footprint (this is a real limiting factor for automotive industry where the footprint size and shape are imposed by the design of the whole transfer line), or the necessary use of multi-*dof* passive joints (Universal of Ball joints) that must be extremely rigid backlash free, *and* compact;
- ✓ **Some factors are common to all 6-*dof* fully parallel mechanisms**, such as, for instance, the complex relationship between orientation range and position (users need a constant orientation range over the workspace), or the fact that one have to pay for 6 controlled chains while using only 5 Cartesian *dof* (3 translations, 2 rotations);
- ✓ **Some factors are due to the use of telescopic legs** (the *U-P-S* chains, with an actuated *P* joint). This point can really become a keystone in a machine-tool for several reasons:
  - ✓ **The heavy moving bodies** involved in the mechanism include ball screws, motors, position sensors, cables, and so on. This could be heavy and decrease the dynamic capabilities;
  - ✓ **The ball screw is not rigidly fixed** on a frame and thus offer poor vibration property in comparison with the same piece of equipment installed on a classical x-y-z machine-tool;
  - ✓ **Thermal energy** is produced in the motor (and, at a lower level, in the ball screw nut) and cannot be evacuated easily to large bodies with large thermal capacity (i.e. the frame). This could decrease the long term accuracy without complex thermal compensation;
  - ✓ The easiest way to install a **position sensor** is at motor level; in that case a large uncertainty is introduced in the measuring system since nothing is measured about the ball screw real behavior. A solution consists of course in placing a measuring system directly inside every telescopic leg, but this is complex and dramatically increase the cost;
  - ✓ The telescopic legs cannot be easily by actuated by high-power **linear drives** which are to date the most efficient way to drive a high performance machine-tool.
- ✓ Finally, **some factors are not related to scientific issues**, such as the fact that parallel mechanisms in machining are much younger that their serial counterparts and thus require time to be accepted by the industrial community.

So, if one takes into account all those drawbacks and limitations, must we discard parallel mechanisms for high performance uses? We do not think so. We rather expect parallel mechanisms to be part of the machine-tool industry future, assuming that not only hexapods are considered.

3 Non-hexapod fully parallel solutions

Among the possible directions of research are the non-hexapod fully parallel machines. In the late 80's, a new field of research and applications has been opened by Clavel who proposed the famous Delta structure [3] as a base for a "family" of parallel machines dedicated to high-speed applications (Figure 3). This has been the first real commercial success for a parallel machine in industry, and its "linear" version (Figure 4) is now the base of the fastest machine-tool ever produced by industry: UraneSx (Figure 5) is capable of acceleration ranging 3.5 up to 5.0 g's!

In the same family of machines is the Hexa [6] robot (Figure 6)and, HexaM [7], its machine-tool version created by Toyoda (Figure 7). This 5-axis machine uses only brushless motors and ball screws but can reach 2.0 g's acceleration!

The ETH's Hexaglide (Figure 8) is intended to offer the same kind of advantages plus the opportunity to get an "unlimited" range of motion along one axis (this is a key feature for aeronautic machinery where very long objects must be machined).

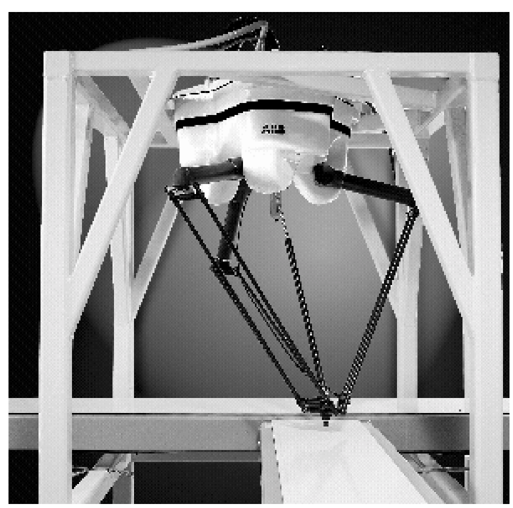

Figure 3. Delta (ABB)

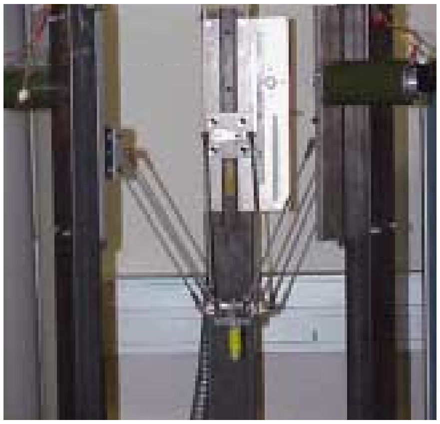

Figure 4. Linear Delta (LIRMM prototype)

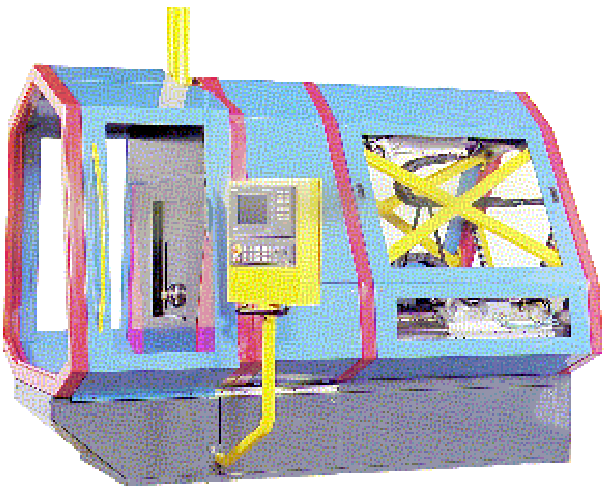

Figure 5. UraneSx (Renault-Automation)

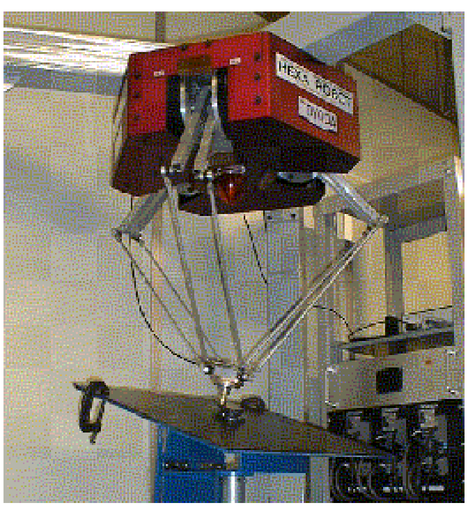

Figure 6. Hexa (Tohoku University prototype)

Figure 7. HexaM (Toyoda Machine Works)

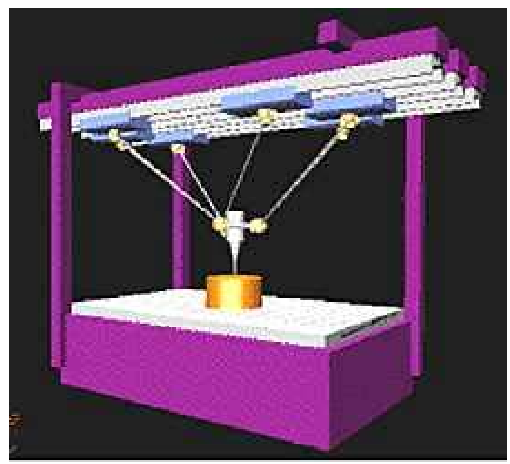

Figure 8. Hexaglide (ETH, Zurich)

4 Hybrid machines

Considering that some limitations are indeed due to the use of fully-parallel mechanisms, it is appealing to investigate architectures based on hybrid arrangements where serial and parallel concepts are combined.
This has been already achieved on Hexel where a serial "wrist" is mounted on an Hexapod. This solution offer a large range of orientation and then suppress one of the important hexapods drawbacks ; however, the price to pay is a 8-motor machine for a 5-axis use.

With a completely different approach Eclipse (Figure 8) solve the problem in an elegant and smart way [11], but could suffer from its 7-motor architecture, and the tricky control method mandatory to overcome motions through "overmobility" singularity.

Figure 8. Eclipse (Sena/ Seoul National University)

An appealing alternate solution in the hybrid machines family is to propose machines with no more dof than needed. This explains the success of Neos Robotics approach with Tricept, based on a parallel Tripod, combined with a passive chain, and equipped with a serial "wrist".

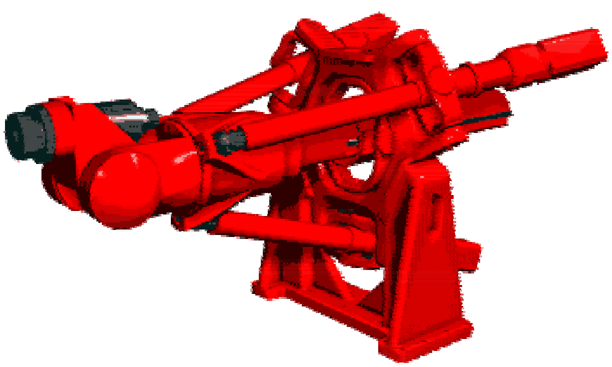

Figure 9. Tricept (Neos Robotics)

Even more consistent with the key sentence: "if it's too hard to make it parallel, make it simple", are the 3-axis machines imagined by Honda Engineering in Japan, or the WZL in Germany (Figure 10).

There are hybrid machines in the sense that the follow the Right-Hand/Left-Hand robotic concept: some degrees of freedom are provided by a parallel mechanism carrying the spindle, and the remaining *dof* are installed on the table carrying the work-piece! Such machines can clearly be modified so that they do not suffer from the drawbacks of telescopic legs and rely on high performance linear drives fixed on the frame, instead.

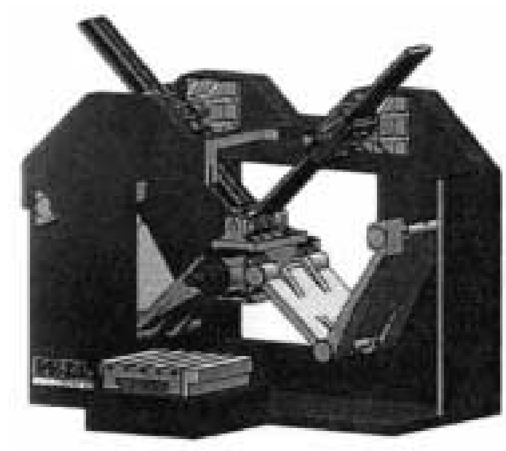

Figure 10. M-Konzept (WZL, Aachen)

5 H4 and other hybrid machines

H4 family. Following the same ideas, we strongly believe that there is a need for equipment providing more than 3 *dof* arranged in parallel *and* based on simpler arrangements than 6-dof structures: one can equip the spindle with 4 *dof* and let the work piece be moved by an additional 5th axis.
Considering this important goal, it is amazing to remark that only few efforts have been devoted in the past to 4-*dof* parallel mechanisms. Apart from Koevermans flight simulator [12] and Reboulet 4-dof wrist [13], which both provide 3 rotations and 1 translation, we can mention few hybrid (that is to say, non fully-parallel) mechanisms as in [14] or [15].
The general concept we propose is to build a fully-parallel mechanism with no passive chain, able to provide high performance in terms of speed and acceleration. Those considerations lead to three important consequences: the mechanism is based on 4 independent chains between the base and the nacelle; each chain is actuated; each actuator is fixed on the base. Such ideas have already proven their efficiency on high-speed equipment such as Delta, Hexa and HexaM .
Knowing the advantages of this family of mechanisms we propose to keep the same of kinematic chains, that is either:

- ✓ P-(U-S)$_2$'s chains, that is to say a Prismatic actuator fixed on the frame, connected to two U-S sub-chains parallel to each other (Linear Delta type);
- ✓ P-U-S chains (HexaM type).

We have shown [16] that this could be arranged in different designs:

- ✓ Symmetrical design, based on four identical P-(U-S)$_2$'s chains, which requires the nacelle to be equipped with two additional passive pivot joint;
- ✓ Asymmetrical design based on two P-(U-S)$_2$'s chains, and two P-U-S chains, with a simple rigid body for the nacelle.

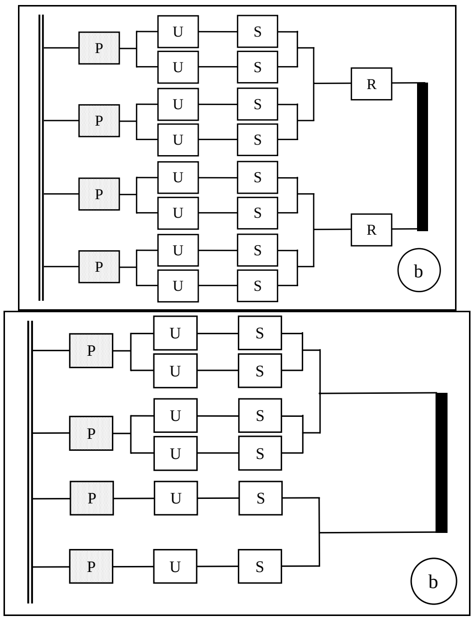

Figure 11. Symmetrical and asymmetrical designs.

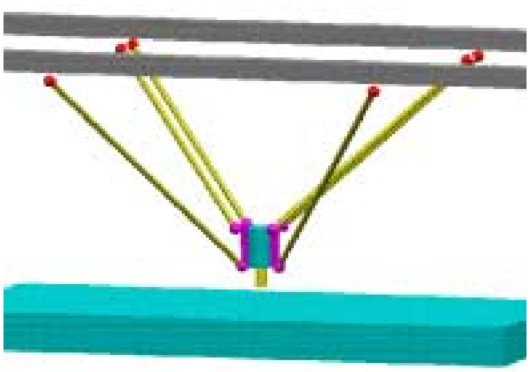

Figure 12. Asymmetrical version of H4, providing three translations (X,Y,Z) and one rotation (B) in parallel. The fifth axis (rotation A) is provided by a* serial *rotational axis.

2-*dof* parallel module. Another possible track of research is offered by extremely basic mechanisms used as independent modules in construction of machinery. For example, in wood cutting industry, where cutting forces and accuracy are relatively limited (and thus stiffness requirements are limited as well) one can imagine a 2 dof planar parallel mechanism providing X and Y motions for a lathe, or Y and Z motions for a machining center.

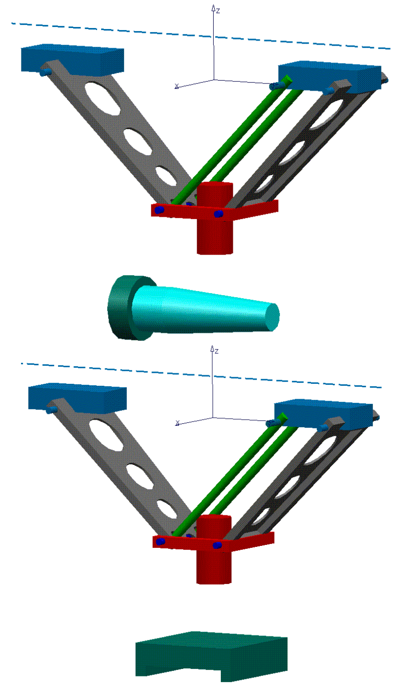

Figure 13. A parallel 2dof planar mechanism is used as a "module" for a lathe, or a machining center.

3-*dof* module with unlimited rotation. Taking advantage of the previous mechanism simple design (no multi-*dof* passive joint!), we propose to consider planar mechanisms offering 2 translations (Y and Z) and one rotation (A) in parallel, and to combine them with one additional serial motion (B rotation) plus a moving table for X translation (this provides the needed *dof* for a 5-axis machine as in Figure 14).

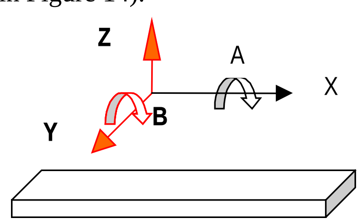

***Figure 14. 5-axis machine* dof.**

With such a machine, one can consider machining full size car models, where ranges of motion along X and Y are very large (along Z, it is possible to accept a smaller range of motion if the model is split in several slices, see Figure 15).

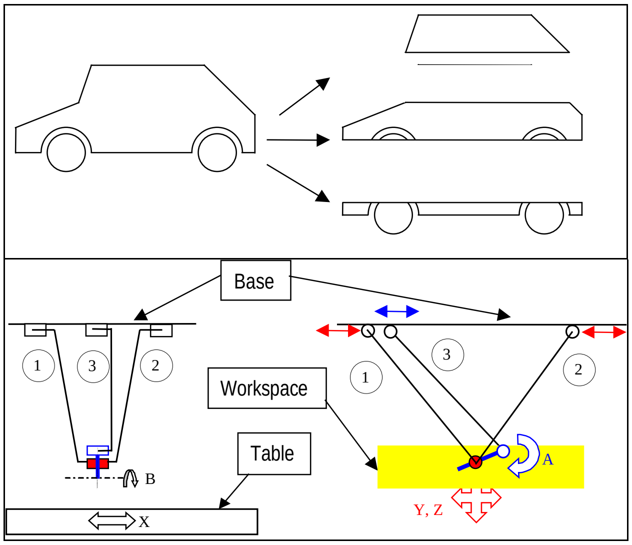

Figure 15. Making car models with a PKM.

The necessary range of motion in orientation is extremely large for such applications. With classical solutions, over-mobility singularities occur after only a small orientation (typically 30 to 45 degrees). To overcome this problem, we propose to add a redundant leg as shown in figure ??. The redundant (actuated) chain A3-B34 leads to a singularity free system since it is impossible to have in the same time A4-B34 and A3-B34 aligned with B12-B34. Of course, a special control system must be set up for this system to face with actuation redundancy.

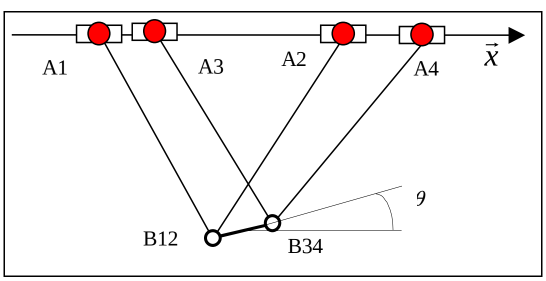

Figure 16. Redundancy to get a larger range of motion.

6 Conclusion

Hexapods have been very seriously investigated and can serve well in many applications; however, it seems that they have some drawbacks that could impair their interest for high performance machine-tool industry. Simple non-hexapod machines, and hybrid machines may be the base of new advances for parallel machine-tools of the future. Based on two simple design choices (motors on the base, legs with constant legs) we have recalled it is possible to build efficient machining centers (e.g. Urane SX with linear Delta arrangement), and efficient machines for die and mould (HexaM or Hexaglide). We have also shown it is possible to build other mechanisms with the same technology in a "hybrid machine" vision. All together, systems with 2, 3 4 or 6 dof can be imagined.

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