CONCEPTUAL DESIGN OF A TRANSLATIONAL HYBRID MECHANISM FOR AGILE MANUFACTURING

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Résumé

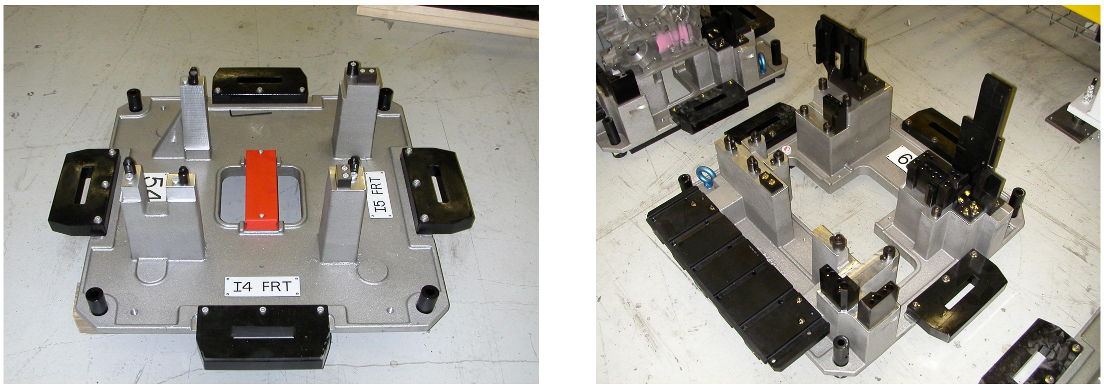
L'utilisation de palettes est une pratique courante et bien instaurée dans la fabrication des moteurs de voiture. L'inconvénient des palettes est qu'elles doivent être conçues et fabriquées à nouveau lorsque la pièce qu'elles doivent supporter est modifiée. Cette opération est coûteuse et entraîne des pertes de temps considérables. De plus, la reconstruction des palettes limite la souplesse du processus de fabrication. Dans cet article, une palette reconfigurable qui permet de supporter toute une famille de blocs-moteurs en aluminium est présentée. L'élément clef de cette recherche est l'utilisation de mécanismes parallèles ou quasi-parallèles dans le développement de la palette ajustable. Les mécanismes parallèles sont reconnus pour leur rigidité structurelle élevée (qui augmente de beaucoup le rapport charge utile sur masse propre du mécanisme) et leur grande précision. La palette ajustable présentée dans cet article peut amener des améliorations significatives dans l'industrie de l'automobile en éliminant le besoin de reconstruire les palettes.

Abstract

The use of fixtures in the manufacturing of automobile engines is a well established practice. The drawback of fixtures is that they must be redesigned and rebuilt whenever the part that they are supporting is modified. This operation is tedious, costly and limits the agility of the manufacturing process. In this paper, a flexible fixturing system accommodating an entire family of lightweight aluminum engine blocks is presented. The key element of this research is the use of parallel or quasi-parallel mechanisms (PMs) in the development of the fixturing system. PMs are known to have high stiffness, high payload and high precision qualities. By virtually eliminating the need for the redesign of fixtures, the flexible pallet presented in this paper may lead to significant improvements in their use in automobile manufacturing.

1 Introduction

The use of fixtures in the manufacturing of automobiles is a well established practice. In the manufacturing of engines for instance, pallets (see figure 1) are used to support the engine blocks through the assembly process. The drawback of such fixtures is that they must be redesigned and rebuilt whenever the part that they are supporting is modified. This operation is tedious, costly and limits the agility of the manufacturing process.



(a) (b)

Figure 1: Examples of pallets used in the automotive industry.

In this context, one avenue to be pursued is the development of flexible fixturing systems. A flexible fixture is a complex mechanical component which must, simultaneously *i*) provide stiffness and positioning accuracy when used as a fixture and *ii*) permit repositioning when the geometry of the fixture is to be modified. Typically, the geometry of the fixture is modified every few months. Hence, a flexible fixture can be considered as a special mechanism in which motion occurs very rarely, and which is immobile when performing its main task (holding parts). This is in contrast with industrial robots and machine tools, in which the performance of tasks is mainly associated with motion. Hence, the demands on the flexible fixture are rather special, namely:

1. The mechanism must be movable, but does not have to produce specific trajectories. That is, specific velocities or accelerations are not required during the motion. In fact, the main demands on the motion characteristics are the required ranges of motion (workspace).

2. The workspace of the mechanism must be a cube with edges of 150 mm. This value arises from observations made on the geometry of existing engine blocks.

3. The static positioning accuracy of the mechanism must be relatively high (0.5 mm).

4. The stiffness of the mechanism must be very high once it is locked in position (vertical static load: 2000 N, dynamic impact load in all directions: 2000 N). However, the stiffness does not need to be high when the mechanism is in motion.

5. The reconfiguration of the pallet must be done manually in order to provide a low-cost demonstration of the concept of the agile pallet.

6. The footprint, the weight of the moving parts and the number of components of the positioning mechanism must be minimized.

7. The operation of the mechanism must be simple and safe.

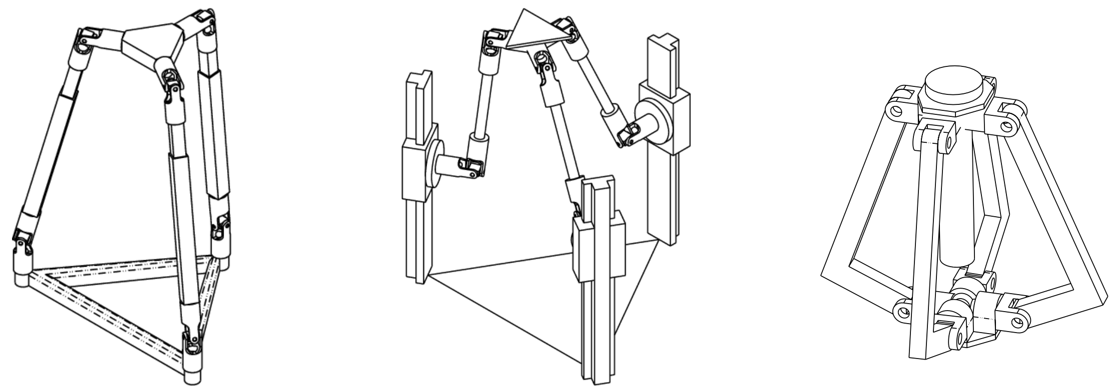
When considering the above characteristics, it appears that PMs are excellent candidates for the development of a flexible fixture. Indeed, PMs have the potential to provide the necessary stiffness and accuracy. A PM is a closed-loop mechanism in which the end-effector (mobile platform) is connected to the base by at least two independent kinematic chains. Several industries are showing a growing interest for devices based on parallel kinematics, because these architectures often provide excellent performances in term of stiffness/weight ratio when compared to traditional serial robots.

2 Possible Kinematic Architectures

The flexible fixturing system to be developed consists of a mechanism with moveable supporting points. Hence, the task to be performed, at each of these points, is associated with a translational motion only (positioning of a point in space). Three-degree-of-freedom (3-DOF) translational PMs (TPMs) have a wide range of applications such as positioning and assembly. There exist several possible architectures of TPMs, some of which have been discovered very recently [1–5].

Among all these TPMs, two fully parallel architectures, the 3-UPU and the 3-PUU vertical mechanism (where U stands for a universal joint and P for a prismatic joint), and a concept of hybrid mechanism were first analysed regarding the demands of the application studied here (see figure 2). The 3-UPU mechanism was studied for the first time by Tsai in [5]. In this mechanism, the fixed base is connected to the platform by three legs, with each leg having a UPU architecture, see figure 2(a). The universal joints are passive, and only the three prismatic joints are actuated. The universal joints can be attached in such a way that the moving platform only undergoes pure translational motion. For the 3-PUU, three inextensible shafts with universal joints on both ends are used to join the end effector to each prismatic actuator, thereby forming the PUU kinematic chains, see figure 2(b). The motion of the prismatic actuators generates the translations of the platform. The alignment of the three actuators vertically provides a large vertical workspace. On the other hand, a hybrid mechanism is a mechanism with serial and parallel components. For instance, a 2-DOF PM mounted on a 1-DOF mechanism constitutes a hybrid mechanism. In our application, the adjustable working envelope needed for the mechanism is almost the same size as the footprint. This demand may be difficult to fulfill with fully-PMs and hence, hybrid mechanisms are also contemplated. There exists several possible architectures of hybrid mechanisms: the one shown in figure 2(c) is only one of the possible architectures.

The analysis of the 3-UPU mechanism has shown that it would be difficult to design such an architecture capable of reaching all desired positions with realistic actuator ranges. Moreover, the UPU and PUU legs have the same drawbacks, namely, the use of universal joints to block rotations. Each of the three legs blocks a rotation with the U-U combination. If clearance appears in the joints, the resulting motion at the end effector will easily exceed the desired accuracy (see section 1, item 3). To join the base to the end effector, these mechanisms use four revolute joints in series. This means that four clearances are added to reach the end effector. The use of revolute joints, as in the four-bar linkage hybrid mechanism, does not lead to this clearance sensitivity. The parallelograms use only two revolute joints in series that are in parallel to two other revolute joints.



(a) (b) (c)

Figure 2: Translational mechanisms previously analyzed (a) 3-UPU (b) Vertically actuated 3-PUU (c) Hybrid mechanism.

A hybrid mechanism also has one completely decoupled direction, which increases the simplicity of the architecture and the dexterity. The dexterity characterizes the capability of the PM to perform precise motion at the end effector. The dexterity is a local property that changes throughout the workspace. From the above remarks, it is readily observed that a hybrid mechanism constitutes an effective solution to produce the 3-DOF positioning mechanism. The next sections address the kinematic and mechanical design of a TPM based on the hybrid architecture introduced above.

3 Kinematic Design of the Hybrid Mechanism

The proposed hybrid architecture, represented in figure 2(c), is composed of a 1-DOF vertical translation system mounted on top of a 2-DOF TPM. The new architecture is based on a 2-DOF PM using planar four-bar parallelogram linkages. Two parallelogram linkages are coupled to create a 2-DOF TPM (see figure 3(a)).

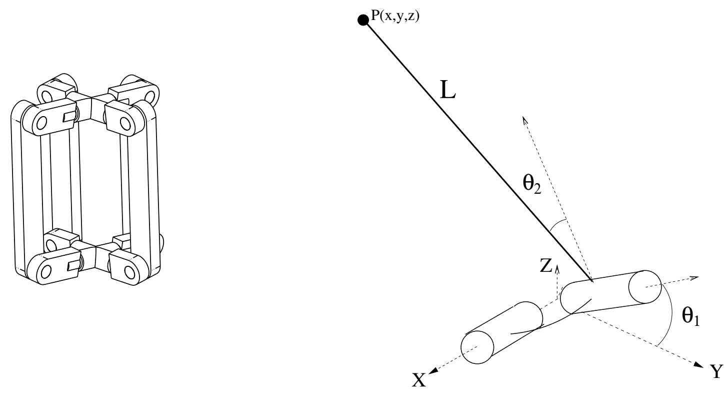
The motion of the upper platform is similar to the displacement of a point on a sphere with the top platform undergoing pure translations. This architecture is similar to a leg composed of a U-joint – member – U-joint arrangement. However, because of the offset between the revolute joints, the proposed architecture is less sensitive to the clearance in the joints. The position of the center point of the platform is given in terms of the angles corresponding to the two degrees of freedom shown in figure 3(b) as :

$$p_x = L \sin\theta_2 \quad (1)$$

$$p_y = -L \sin\theta_1 \cos\theta_2 \quad (2)$$

$$p_z = L \cos\theta_1 \cos\theta_2. \quad (3)$$

The length of each leg of the model is chosen as L=200 mm. This allows the mechanism to reach all the required x-y workspace (±75 mm, see section 1, item 2) with small angular ranges of motion of the joints in the two directions (±24° from the normal direction). Figure 4 shows the workspace



(a) (b)

Figure 3: (a) 2-DOF PM containing the planar four-bar parallelogram (b) Kinematic model of the 2-DOF PM.

of the 2-DOF PM. The drawback of this architecture is the variation of the z coordinate when displacements are performed in the x-y directions. However, with this angular range of motion, the variation is of the order of only 30 mm. To obtain the 150 mm range needed in the z direction, the additional 1-DOF mechanism should have a range of motion of 150 mm + 30 mm = 180 mm. The 1-DOF mechanism is simply a shaft sliding vertically in the platform of the 2-DOF mechanism. The shape of the legs is designed to avoid interferences between the legs and the vertical mechanism.

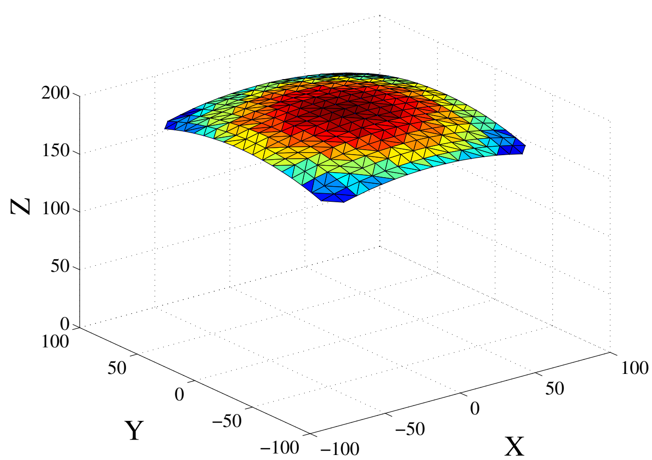


Figure 4: Workspace of the 2-DOF TPM.

4 Mechanical Design of the Positioning Mechanism

The functional design of the positioning mechanism including all the mechanical components is presented in figure 5. The components are designed to minimize the deformations under the prescribed loads (see section 1, item 4), thereby leading to the required stiffness. As opposed to the four-legged concepts illustrated in figures 2(c) and 3(a), the proposed design is a three-legged structure, which leaves more space for the engine block and assemblers than the four-legged version. The kinematics are the same as for a four-legged structure since the third leg is perpendicular to the plane formed by the other two legs. The locking mechanisms are important features of the mechanism used for the fixtures. Indeed, the positioning mechanism must be locked once in position to ensure that no motion will occur when moving the pallet on the assembly line. Only two locking mechanisms are needed to block all motion of the 2-DOF mechanism, but using one locking mechanism on each leg leads to a better distribution of the forces. The three legs are locked using a passive axis located inside the legs with simple friction-based devices blocked with a screw. Once in position, the three screws are locked to avoid any motion. The platform at the top of the mechanism is wider in the direction of the single leg in order to reduce the load due to dynamic impact in that leg. The shaft forming the 1-DOF vertical mechanism is also locked with a friction-based device using a screw. With this design, the operator can easily move the end-effector in the three directions x, y and z at the same time. Experiments have shown that the friction-based locking mechanisms provide sufficient forces to prevent motion under the applied loads. In a practical application, the manual positionning of the mechanism would be assisted by an optical or mechanical measuring system in order to provide the positioning accuracy.

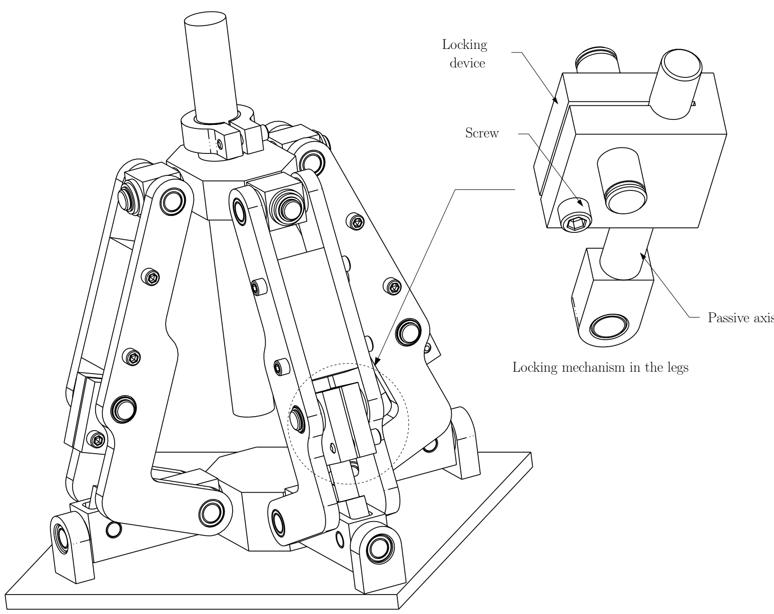
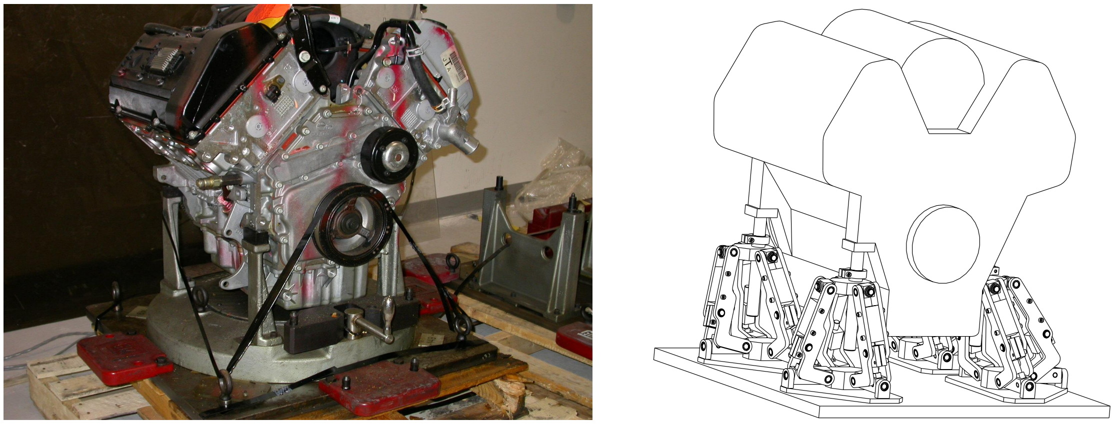


Figure 5: The functional design of the positioning mechanism.

5 Example of Complete Flexible Fixture System

The possible configurations that the flexible fixture system can assume depend on the position of the four positioning mechanisms on the base of the pallet and on the position of the engine above the pallet. A study of different engine block assemblies is required to optimize the position of the four positioning mechanisms. Figure 6(a) shows a pallet used in the automotive industry and its corresponding engine. The example of complete flexible fixture presented on figure 6(b) is inspired from the engine and pallet of figure 6(a). The pallet system built using the hybrid mechanism presented in the previous section leaves sufficient space for accessing the engine and presents no interference between the supporting mechanisms and the engine.



(a) (b)

Figure 6: (a) An engine and its pallet used in the automotive industry (b) Example of complete flexible fixture system.

6 Conclusion

This paper presented a flexible fixturing system that can accommodate an entire family of engine blocks. A flexible fixture is a complex mechanical component providing stiffness and accuracy when used as a fixture, but also having motion capabilities when the geometry of the fixture is to be modified. The pallet system uses four 3-DOF hybrid mechanisms as supporting points for the engine block. The selected hybrid architecture is composed of a 1-DOF vertical translation system mounted on top of a 2-DOF TPM. The functional design of the 3-DOF hybrid mechanism is a three-legged structure with a vertical shaft sliding in the moving platform. Once in position, the three legs and the shaft of the positioning mechanism are locked with simple friction-based devices using a screw. It is anticipated that the results obtained in this research may also find applications in other areas, such as flexible assembly lines for other products, high-accuracy positioning devices and manually operated manipulators.

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