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Optimal custom design of both symmetric and unsymmetrical hexapod robots for aeronautics applications

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ABSTRACT

The Stewart parallel mechanism is used in various applications due to its high load-carrying capacity, accuracy and stiffness, such as flight simulation, spaceship aligning, radar and satellite antenna orientation, rehabilitation applications, parallel machine tools. However, the use of such parallel robots is not widespread due to three factors: the limited workspace, the singularity configurations existing inside the workspace, and the high cost. In this work, an approach to support the design of a cost-effective Stewart platform-based mechanism for specific applications and to facilitate the choice of suitable components (e.g., linear actuators and base and mobile plates) is presented. The optimal design proposed in this work has multiple objectives. In detail, it intends to maximize the payload and minimize the forces at each leg needed to counteract external forces applied to the mobile platform during positioning or manufacturing, or, in general, during specific applications. The approach also aims at avoiding reduction of the robot workspace through a kinematic optimization. Both symmetric and unsymmetrical geometries have been analysed to show how the optimal design approach can lead to effective results with different robot configurations. Moreover, these objectives are achieved through a dynamic optimization and several optimization algorithms were compared in terms of defined performance indexes.

1. Introduction

Nowadays, the assembly process of aircrafts highly relies on skilled human operators that are necessary in all the assembly phases, such as part positioning, drilling, fastening, riveting, and quality assurance. With the introduction of the composite and reinforced carbon fiber technologies into the manufacturing process, the aeronautics industry is experiencing an increase of the non-added value operations (i.e., temporary assembly to check gaps, shimming, dismantling, tool handling, drilling, and fastening) that lead to an increase of the overall manufacturing costs and, principally, of the overall process time. In this field, the research is focusing on the development of cost efficient part manufacturing and assembly processes of composite, metal and hybrid airframe structures. Their introduction in the manufacturing process aims to the reduction or the total elimination of the most time consuming and hence expensive operations. In order to achieve a lean manufacturing process and ensure the accuracy and the repeatability required in the aeronautics standards, new co-shared manual and automated operations are under investigation. Several riveting and drilling solutions that make use of complex and heavy multi-function end effector and oversized industrial robots have been proposed in the literature [1–8], but only few solutions have been proposed for the aeronautics part positioning problem [9–11]. The conventional assembly process requires that the parts to manufacture are positioned into welded mechanical structures, called fixtures. A fixture is a work-holding or support device used to securely locate (in a specific location or orientation) and support the work, ensuring that all parts produced using the fixture will maintain conformity and interchangeability. Therefore, the fixtures are designed on the base of the considered aircraft subsection, e.g., wing-box, fuselage; changes in the held parts could result in changes in the fixture that could cause an increase of the manufacturing process costs and introduce a delay in the overall manufacturing line. The ability to change the configuration of an airframe assembly tool in order to assemble different products within a product family becomes a very important feature. Reconfigurable tooling should reduce the number of tools on the workshop floor and, thereby, save floor space; it should simplify the build-up and change of assembly tools and drastically reduce

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lead time in tooling design and build-up. The solutions proposed in the literature use standardized profiles, which make the fixtures possible to re-cycle the parts, and as the parts in the fixture are not welded, they can be adjusted and provide some flexibility. There also exist techniques to achieve reconfigurability by using the so-called pogo sticks, which can change the configuration to adapt themselves according to the specific airframe structures [12]. In recent years, the research is focusing on the development of adaptive fixtures which make use of parallel robots, i.e., Stewart platform-based robots, to position or to hold the parts during the manufacturing/assembling phases [13]. In comparison with a serial manipulator, the Stewart parallel manipulator, capable of providing six degrees of freedom (DOF) movement, comes up with some advantages [14] that make them the optimal solution for these types of applications:

- high strength and stiffness-to-weight ratios can be achieved since the links do not carry moment loads but act only in tension and compression;
- positioning of the end effector is performed by actuators acting in parallel, resulting in a total force and moment capability greater than each individual servomechanism;
- moving only the end effector in space rather than massive servomechanisms results in economy of power, excellent dynamic performance, and low manipulator inertia;
- high accuracy and precision is possible since actuator errors are not magnified by lengthy linkages.

In fact, the Stewart platform, also called hexapod, is used in many applications where high positioning accuracy and high stiffness are required, i.e., flight simulation [15], spaceship aligning, radar and satellite antenna orientation [16,17], rehabilitation applications [18], robots [19], and parallel machine tools [20,21]. Unfortunately, there are factors that limit and complicate the design of such a mechanism. First, the limited workspace that reduces the number of tasks the robot can execute and the singularity configurations existing inside the workspace in which the manipulator gains one or more degrees of freedom and therefore looses its stiffness. The closed-loop nature of parallel mechanisms generates complex singularities inside the workspace, which makes the workspace analysis and the trajectory planning of parallel mechanisms a challenge. Moreover, although the versatility of the hexapod has been recognized, its acceptance by industry as production equipment has not yet occurred. Some obstacles to this include the high cost and unproven performance in a production environment for a specific task. Hence, the design of an efficient approach that allows us to maximize the robot workspace, reduces the singularities inside the workspace, optimizes the design of the parallel platform reducing the hexapod costs, and keeps limited its encumbrance becomes a very important issue.

2. Problem formulation

In order to better understand the versatility of the use of the Stewart platforms in the aeronautics assembly/manufacturing process, a brief review on the general aeronautics build philosophy is reported. The conventional vertical manual approach used in the aircraft assembly is a time-consuming and labor-intensive process that requires several and subsequent phases of assembling and disassembling in order to accurately position the aeronautics parts. Once all the parts are positioned inside the fixture, an intensive shimming phase is carried out in order to increase the coupling before the clamping and the drilling phases and, thus, to ensure that the final product respects the tolerances specified in the mechanical drawings. After the shimming phase, a clamping phase is carried out by using a large number of temporary fasteners to assure the perfect coupling between the parts before the drilling phase. Finally, the drilling and the riveting tasks can be performed. The aeronautics researchers have proposed new technologies to reduce the shimming time, e.g., by automatically creating the shims before mounting the parts on the fixture. Moreover, as already illustrated in Section 1, valid automated solutions for aeronautics riveting and drilling have been proposed [22]. The positioning problem, instead, is an open research field and only few applications using hexapods inside the aeronautics fixture can be found [13]. An adaptive and flexible fixture constituted by Stewart platforms can be exploited, for example, in the positioning and holding of the airframe parts during a manufacturing process, e.g., riveting and drilling. The spar and rib positioning are two of the many applications in which the use of the hexapod can be exploited. In both the aforementioned problems, it is required that the airframe part is accurately positioned into the fixture, with a perfect coupling between the other parts, i.e., upper and lower covers, ribs and stringers. Furthermore, in the positioning phase, it must be guaranteed that the moved part does not collide with the other parts in the fixture to prevent damages and possible material deformations. When the part is in its final position, often, a drilling process is carried out through more coupled parts in order to reduce the coupling problems that may occur in the next assembly phases.

In this scenario, a lot of machining tools are involved, so, it is important to reduce the encumbrance of the parallel machines used to keep and move the parts during the entire assembly process in order to avoid the insertion and removal of the tool inside the airframe fixture and collisions between the machining tools. At the same time, it is important to take into account the external forces acting on the platforms during the process, and the dimensions and the weight of the part to position for better dimensioning the platforms and to satisfy the strict aeronautics manufacturing requirements. High forces applied on the robot top plate, e.g., during the drilling phase or the riveting phase, can deflect the robot end effector and, then, reduce the positioning accuracy in such a way that the resulting holes are outside of specified tolerances. Moreover, in order to reduce the fastening time and, at the same time, ensure high manufacturing quality, the parallel robot can be exploited to apply a clamping force to airframe parts opposing to the drilling or riveting actions through the use of a force sensor and a force control.

Fig. 1 shows a concept of a flexible/adaptative fixture designed to overcome the aforementioned issues (the 3D drawings are parts of the demonstrator of the LOCOMACHS project). In particular, the picture on the top shows a possible use of three cooperative Stewart platforms for the spar positioning; on the bottom image, a Stewart platform is used into a flexible fixture for positioning a rib into the wingbox during the assembly process.

The presented work provides an approach to support the design of n hexapod machines to be used in such applications that impose strict criteria in terms of high positioning accuracy and, at the same time, dimension constraints and low cost. In this context, it is important to take into account also the forces acting on the platform during the whole task. Therefore, the main issue is the reduction of the size of the platform and, simultaneously, increase the maximum external force that can be counteracted by the platform during a machining task. This is not a trivial issue, since the reduction of the platform dimensions implies also the reduction of the actuator dimensions, and, thus, of their maximum load. Moreover, by reducing the plate dimensions, the leg configuration changes, and this could lead to a reduction of the stiffness and the accuracy of the parallel robot. According to the previous discussion, an alternative