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Research Paper

Sizing the Actuators for a Dragon Fly Prototype

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Abstract. In order to improve the design of the actuators of a Dragon Fly prototype, we study the loads applied to the actuators in operation. Both external and inertial forces are taken into account, as well as internal loads, for the purposes of evaluating the influence of the compliance of the arms on that of the "end-effector". We have shown many inadequacies of the arms regarding the stiffness needed to meet the initial design requirements. In order to reduce these inadequacies, a careful structural analysis of the stiffness of the actuators is carried out with a FEM technique, aimed at identifying the design methodology necessary to identify the mechanical elements of the arms to be stiffened. As an example, the design of the actuators is presented, with the aim of proposing an indirect calibration strategy. We have shown that the performances of the Dragon Fly prototype can be improved by developing and including in the control system a suitable module to compensate the incoming errors. By implementing our model in some practical simulations, with a maximum load on the actuators, and internal stresses, we have shown the efficiency of our model by collected experimental data. A FEM analysis is carried out on each actuator to identify the critical elements to be stiffened, and a calibration strategy is used to evaluate and compensate the expected kinematic errors due to gravity and external loads. The obtained results are used to assess the size of the actuators. The sensitivity analysis on the effects of global compliance within the structure enables us to identify and stiffen the critical elements (typically the extremities of the actuators). The worst loading conditions have been evaluated, by considering the internal loads in the critical points of the machine structure results in enabling us the sizing of the actuators. So that the Dragon fly prototype project has been set up, and the first optimal design of the arms has been performed by means of FEM analysis.

Keywords: Vibration suppression method; parallel manipulator; flexible-link robot; compliant behavior; robot-environment interaction; optimal trajectory planning; input shaping method.

1. Introduction

Robotics is moving increasingly towards applications that involve the interaction between the manipulator and the surrounding environment. There follows the need to develop manipulators that have a flexible behavior, in order to safely interact with the surrounding environment [1-3]. This can be achieved, both on the software, through the controller, or, and on the hardware, by using flexible links. The "yielding" behavior of the manipulator is discussed in order to define a strategy for planning suitable trajectories that allows positioning in the work area by limiting the occurrence of vibrations, using the Input Shaping technique. The obtained results by our simulation seem to be enough good, thus encouraging future experimental tests on the real Manipulator.

The PKMs are mainly used in traditional robot fields (pick and place), and for high precision positioning. These applications exploit some of the characteristics of parallel kinematic chains, in particular, the lightness of the structures and consequently their low inertia which allows high speeds and accelerations (up to l0g for the Demaureux Delta robot). On the other hand, the high load-to-weight ratio, combined with the intrinsic structural stiffness given by the parallel link, makes the use of a PKM suitable for high precision positioning [4-7]. These peculiarities make them suitable to be used to handle heavy objects with rapidity and precision or for objects under high values forces, thus enabling the development of many applications: such as motion simulation (flight, tank) medical applications (surgical position instruments), space applications (coupling systems), machining, assembly and disassembly.

The first prototypes of Hexapod machines (the Variax by Giddings & Lewis, the Octahedral by Ingersoll) were presented at the international machine exhibition (Chicago, 1994) They were enthusiastically welcomed as the new generation of machine tools, thanks to their specific characteristics that should have guaranteed better performance, namely:

- high load-bearing-to-weight ratio (the payload is carried by several links in parallel);
- non cumulative joint error;

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- high structural rigidity (the load is held by parallel connections and in some structures the stresses are limited to those of tension-compression);
- modularity (each kinematic chain is made up of the same physical modules);
- positioning of the motors near the fixed base;
- simpler solution to the inverse kinematic problem.

All these advantages lead the machine tool builders and researchers to study PKM applications also for the 5-sided machining, a field where the traditional machine tools have not achieved the expected results. Since its debut in 1994, several prototypes of parallel kinematic machine tools have been developed and they are still under evaluation. However, the adoption of a PKM leads also to some disadvantages: PKMs suffer from singular configurations, a well-known problem in the field of robotics, small workspace compared to the size of the manipulator, a complicated direct kinematic solution, and, consequently, more difficult control techniques [8-11].

The kinematic and dynamic behavior of the machine is strongly influenced by tolerances, and machining and assembly errors and therefore, particularly for machining applications, calibration strategies must be defined and consolidated.

In this paper, after a short analysis on the kineto-static behavior of parallel kinematic mechanisms (PKM), the general tools and optimization criteria given by industrial process requirements are provided for the design of a PKM. The theoretical problems related to the study of parallel kinematics mechanisms are also presented and their usability as innovative processing systems is investigated. First, the peculiarities of PKM with different morphological configurations were analyzed, by investigating also their application potential [12, 13].

In addition, the main research topics on PKM were investigated and an updated re-view of the current state was discussed, examining recent advances in systematic design, kinematics, error analysis, calibration and control; Various applications for PKMs were discussed, highlighting the fact that the gap between theoretical and practical advantages has not yet been filled. Although parallel kinematics machines have been well known since the early 1960s, only in the last decade there has been an increasing great interest developed in the application of these mechanisms in industrial production.

The present work proposes a new approach for planning the trajectories of manipulators with planar parallel kinematics, flexible links, that have to perform Pick & Place operations. In recent years, interest in applications in which the manipulator interacts with the surrounding environment has gradually increased. This happens because robots are increasingly used in areas where cooperation with human operators is expected [14-16]. A typical example is the use of a manipulator in industrial plants; in the sur-rounding environment there may be the presence of operators, other manipulators, or any type of mechanical elements.

The fact that safety is guaranteed during the execution of an operation is implemented by ensuring that the manipulator itself has a yielding behavior. This can be done by introducing compliance on the joints, or by introducing compliance on the structure itself, or parts of it, for example by introducing flexible links. In this way it is possible to limit the damage caused by accidental contact between robot and operator or between robot and work environment, thus reducing the risk of breakage or damage [17, 18].

Although the considerable advantages in terms of safety above all, as a consequence of a positioning carried out within the work area, the end-effector begins to vibrate, due to the intrinsic flexibility of the system. This problem was solved by developing a new technique for planning trajectories in the manipulator workspace. The developed technique foresees to split the complex problem that consists in the generation of a trajectory in the plane (which admits infinite solutions) into two sub-problems: the generation of the path and the choice of the law of motion to be applied to it.

Path and law of motion are generated by taking into account the knowledge of the elastic properties of the system, which are mapped over the entire work area. The technique is first developed on an "ideal" manipulator, i.e., with a configuration designed for the only purpose of highlighting certain kinematic and dynamic characteristics. This is done in order to make use of analytical tools, which enable to understand the problem and the proposed solution, but also to underline the fact that the approach has been developed for an entire "class of manipulators" having certain features. Subsequently, the proposed technique is tested, through simulations with the commercial multibody software Adams MSC, on the Robot 5R 2DOF, manipulator with two degrees of freedom, with two flexible links [19, 20].

Moreover, several tests were carried out to evaluate the internal loads and the actuators strain, under external loads, gravity and some additional inertial effects. In addition, the consequences of the machining and the assembly error on the accuracy of the machine were estimated, as well as the compliance at the extremities of the structure which are due to the compliance of the entire system, in order to verify if the prototype meets the initial requirements.

The organization of this paper is as follows: in section 2, some fundamental problems arising in robot design, such as loading conditions, VPE-PKM method and architecture are carefully discussed. Section 3 deals with the actuators sizing, thus discussing machine errors and analysis of internal loads. Control of actuators is discussed in section 4, by focusing on PKM, and the structural characteristics and calibration. In section 5, the dragon fly prototype project is reported with the corresponding FEM analysis and design. In the last section 6, conclusions of some open problems and future perspectives are given.

2. Problems Arising in Robot Design

Robots are composed by four functional units, or structures, which operate in synergy and therefore able to guarantee the correct functioning of systems thus being capable of reaching very high levels of complexity. The four structural components are: mechanical, sensory, control and governance.

The mechanical structure includes the devices that enables the robot to perform operations from a fixed location, rather than moving in space. This is the case of the sequences of arms and nodes of the robot body. One of the simplest cases is represented by a single robotic arm, which has a fixed base with departing articulated elements, and in correspondence a terminal instrument (end effector), useful for carrying out a specific operation.

The sensory structure includes a set of sensors for detecting data from the nearby context to transmit them to a governing device which is equipped with computational units.

The control structure includes a series of actuators that activate the robot in order to let it perform the planned operations. The control structure is therefore characterized by some components capable of connecting perception with action, such as motors and pneumatic systems, in addition to the control algorithms that drive the actuators them-selves.

The governance structure, in its minimal configuration, it includes both the data storage and the computational system, which are needed for programming, calculating and verifying the robot's activities. The governance structure usually coincides with the IT equipment, that is the hardware and software for the operation of the machine (operating system, drivers, development environments and application software).

Among the many properties of the considered mechanical system we have the degrees of freedom, which express the level of technological complexity of a robot as regards its movements. This is a topic usually associated with kinematics, due to the fact that a robot is physically defined as an open kinematic chain of rigid bodies connected by joints, which themselves can be prismatic in nature. In general, the number of degrees of freedom corresponds to the minimum number of independent variables which are necessary to univocally determine the position of a point in the space. In the Cartesian coordinate sys-tem, the position is defined by three variables (x, y, z), which become six if we also consider the rotations around the axes. In the case of simple manipulating robots, the degrees of freedom can be limited to six, while they rise considerably in the case of anthropomorphic robots, whose appearance, although stylized, is openly inspired by that of man.

In fact, the total number of degrees of freedom of a robot it results from the sum of the degrees of freedom of each of its components, by taking into account the constraint that reduce the degree. In the case of a humanoid manipulator, it is therefore easy to imagine how it is possible to obtain decidedly high values, if we consider that a robotic hand, often the most complex technological element to engineer, can exceed 10 degrees of freedom, since each finger is made by several articulated segments. Several optimization studies have been performed to improve the operational and functional capabilities of these de-vices.

Different processes of structural design and controller optimization for a PKM robot using different optimization techniques have been investigated by different authors. First, the desired kinematic properties of the robot, such as the position, velocity and acceleration of the end point, were determined by using the inverse kinematics scheme. In fact, with these procedures, an optimization problem has been introduced to minimize the shaking force and moments, and the values of the desired kinematic quantities have been characterized as constraints. All the properties of the robot have been defined as design variables in the input phase and subsequently the results of the considered optimization process have been obtained. The results showed that it was possible to significantly re-duce the shaking force and moment using the optimal design parameters.

It was also observed that the shaking force and shaking moment could be significantly reduced by using such methods with a positive effect on the accuracy of the trajectory to be achieved. Furthermore, the considered optimization methods were compared by using the same number of iterations in the calculations, and thus it was possible to evaluate the method with best results compared to others. This is very important for the designer of a PKM robot.

In the last decade, PKM robots have been widely used in various industries, especially in robotic applications such as industrial assemblies, transportation and positioning, as well as for touch and medical devices. However, in the design of such a mechanism, several problems related to kinematics and dynamics are still unsolved. In particular, the analysis of the working space (including any singular points) and the planning of the trajectory are the main kinematic problems, while the computation and minimization of the shaking forces and torques, together with the torques due to the actuators, are the crucial dynamical problems.

Some authors have addressed the kinematic optimization problem for a micro-parallel robot (two linear actuators and three rotary joints). In general, for fast moving parallel mechanisms, the trajectory planning is also of fundamental importance. In fact, some studies have been done on the movement profiles (constant speed and trapezoidal speed) by using suitable calculation codes. With these methods some authors have succeeded in optimizing the mechanism for laser cutting to accelerate short movements.

High-speed mechanisms are designed to eliminate or minimize shaking forces and shaking moments. It has been noted that an inertial counterweight and a physical pendulum joint can provide a complete balance of force and momentum for a specific case taken into consideration. Furthermore, with this method the conditions for the redistribution of the additional masses, which are necessary to completely balance the inertial loads, were determined. Statistical methods have been also in these studies and, in particular, the most popular stochastic optimization methods are the genetic algorithm (GA), the particle swarm optimization (PSO) and the differential evolution (DE).

These methods have numerous applications for designing both the considered mechanism and the machine. For instance, these methods have been used to optimize the four-bar links, which are in the opening and closing mechanism of the car's trunk lid. Moreover, by the solution of some optimization problems by a genetic algorithm it has been obtained the largest working space.

In recent years, various control algorithms were used for the optimization of the considered device. This approach is slightly different from the previous studies for the following reasons. First, in the solution of the robot manipulator balancing problem, all joint properties, such as lengths, masses, inertias and centroids of the bars, are considered as the optimization parameters. Secondly, in this optimization problem, the largest desired trajectory is plotted in the reachable work area (without singularities) with constraint functions. Thirdly, the characteristics of the developed controller were also obtained through an optimization process. The balancing and control of the manipulating robot could be considered as a single multi-objective optimization problem. However, the combination of these two phases of the problem could make the optimization algorithm more complicated. Hence, the manipulator control problem was defined as a secondary optimization problem.

One of the main goals of Industry 4.0 is to achieve a higher level of operational efficiency and productivity, as well as a higher level of automation. Automation is considered in the manufacturing industry as the main tool to improve the efficiency of the manufacturing processes. In particular, the nanometer-level measurement on the surface of the target object by a machine was considered for automation, but there were major practical problems such as the very high costs involved and the large amount of time required for the measurement. It should be noticed that most of the processes related to micro-roughness and cambering were carried out manually by craftsmen who boast many years of experience and skill.

On the other hand, such craftsmen's skills can be reproduced technically by applying the methods of machine learning and control technologies. Therefore, through robotization it is possible to imitate the skills and abilities of craftsmen through appropriate intelligent algorithms. In particular, a robotic vision system based on an intelligent algorithm for the recognition of micro-roughness on arbitrary target surfaces has already been created. This proposed system proved to be economical, it carried out rapid measurements and was able to autonomously recognize the micro-roughness to improve the efficiency of the production processes. The proposed system has considered some images from various angles with 4 degrees of freedom.

For the considered robot, a vibration suppression method based on fuzzy inference [21] was proposed to improve the micro-roughness recognition rate. To this purpose an electron microscope was mounted on the edge of the robot arm. The images received from the electron microscope were reconstructed by using the stitching method. Then, the merged images were sent to a deep learning network (conventional neural network: CNN) for object recognition. Usually, the robot arm movements are characterized by some vibration and low movement accuracy [22]. However, by using the image recognition training datasets, it is possible to improve the recognition rate by suppressing the vibration of the robotic arm movement [23].

Therefore, a method for robot arm vibration reduction by examining sensing, fuzzy inference, and servo-motor control was proposed to improve the recognition rate of micro-roughness. The sensing module transmitted X-, Y-, and Z-axis acceleration values from the accelerometer mounted on the edge of the robot arm. This module is sending the collected data to the controller via serial transmission. The error values were entered into fuzzy inference. The error is the root mean squared error of the X, Y and Z axes, where the true value is the mean value of the acceleration received by the accelerometer. The output was determined by the Enhanced Iterative Algorithm with Stop Condition (EIASC) meth-od [24].

In image stitching, some feature points were detected in multiple electron microscope images and the matching was done based on these feature points. There results a single high-resolution image of the entire acquired object by stitching each image. In this way the system was able to recognize the micro-roughness on the surface. A deep learning model was also used to perform the object detection. A large number of images containing micro-roughness were required to train the model. For this purpose, image datasets containing micro-roughnesses were created for the training of the considered system.

Furthermore, the transfer learning was also considered, which is a method of transferring a model that has already been used in other applications to train a system for an-other type of problem in order to improve the micro-roughness recognition rate and to re-duce the training time.

In conclusion, it can be said that from a technological point of view, the glimmers of the future of robotics are almost infinite. Taking for granted the continuous evolution of robots already widespreading in the commercial sector and the good level of maturity reached by anthropomorphic robots, not only in the industrial sector, the great challenge will be the creation and control of ever more performing and inexpensive humanoid and android robots, in order to increase their diffusion on the market.

2.1 VPE-PKM Method: Virtual Prototyping Environment for Parallel Kinematic Machines

The adoption of PKMs in the industry can be facilitated by the availability of methodological tools capable of analyzing PKMs of all types in a short time, providing the key data necessary for the design of the machine. The VPE-PKM fulfill these requirements, assessing in a short time not only the work-space that can be reached, but also the efforts of the actuators, the internal loads in the mechanical structure and the effects of the overall compliance of the structure.

The VPE-PKM method was designed to overcome the limitations encountered in the handwriting of equations and to satisfy the following requirements:

1) General. Applicability to any type of PKM, both new and existing

2) Completeness. It should assist the user in the key steps of the mechanical design, responding to application requests: architecture selection, geometry optimization, actuator sizing, design of the mechanical structure.

3) Fast results. It should give answers in the typical short development time of an industrial product. In fact, it should be used in the early stages of a project, when it is necessary to quickly configure and evaluate different architectures.

The VPE-PKM meets these requirements by combining the power of a multi-body software (ADAMS™) with the efficiency of a specific analysis procedure for PKMs (implemented in Matlab™)

Although the VPE-PKM modeling software has been used in this work, it must be remembered that at the current state of the art, there are also other tools which incorporate different design methods into a single development environment. For example, the Solid Geometry Library of the Technical University of Munich has integrated geometric modeling, multi-body simulation, and FEM modeling into a single toolbox in MATLAB [25-27].

2.2 VPE-PKM Architecture

A The kinematic analysis based on the evaluation of the Jacobian matrix is fundamental for the PKM project, but it is not sufficient to complete the analysis of a real machine. In fact, the actuators must not only counteract all the external loads applied to the end-effector (as evaluated by the Jacobian), but must also work to support the weight of the machine, balance the forces of inertia and overcome friction at the joints. It is also important to evaluate the loads in the critical points of the structure. It was therefore decided to develop the VPE-PKM by customizing a general multi-body analysis software with a set of "ad hoc" procedures and related user interfaces dedicated to the virtual PKM prototype [28-30].

The key features of a multi-body analysis package developed by a VPE-PKM are:

- Full and customizable 3D graphical user interface for manipulator modeling and visualization.
- Automatic generation of kinematic and dynamic equations.
- Linearization of the model and generation of a state representation.

The VPE-PKM method strongly increases the effectiveness of the solution by adding the following specific capabilities of a PKM:

- User interface dedicated to a fast and solid setup model (e.g., to define the limits of the joints).
- Analysis aimed at the complete identification of the workspace (e.g., stiffness map-ping according to a grid of points).
- Specific strategies for analyzing a PKM.
- Post-processing of the data detected by the multi-body analysis, using efficient mathematical procedures.
- Complete and intuitive 2D and 3D graphic representation.

The VPE-PKM method also allows the following analyzes:

- Interference analysis: Determination of the current workspace (considering the active and passive limits of the joints).
- Jacobian analysis: Singularity and numerical conditions of the Jacobian.
- Actuator effort: Efforts to the actuators due to external forces, the weight of the ma-chine, the forces of inertia and friction in the joints.
- Error analysis: Tool positioning due to deformations in the structure or machining errors.
- Compliance analysis: compliance at the tool end due to the overall compliance of the structure.

2.3 Evaluation of The Worst Loading Conditions

The kineto-static analysis, based on the evaluation of the Jacobian matrix, is certainly fundamental for the conceptual design of the PKM, but it is not sufficient to evaluate the design of a real machine. In fact, the actuators must not only counteract the external loads applied to the end-effector (as evaluated by the Jacobian), but must also work to support the weight of the machine, balance the forces of inertia and overcome the inevitable friction at the joints [31]. It is also important to evaluate the internal loads in the critical points of the machine structure. The arms are subjected not only to axial loads but also to torsional and above all bending loads. In addition to the determination of the workspace (considering the active and passive limits of the joints and the interference between the arms), and the Jacobian analysis, the following design parameters must be evaluated:

1. Loads of the actuators: due to external forces, the weight of the machine, the inertial forces, the friction of the joints.
2. Loads in the structure due to external forces and machine weight (inertial forces are currently approximated to equivalent external loads).
3. Tool arrangement due to structural deformation or machining errors.
4. Compliance at the tool end due to the overall compliance of the structure.

The last two analyzes are particularly important in determining the required stiffness and maximum compliance required in the joint-arm-joint kinematic chain to meet the initial requirements.

Table 1. Industrial requirements of the Dragon Fly prototype.

Maximum speed of the end-effector	1 m/s
Maximum acceleration of the end-effector	5 m/s²
Maximum force applied	70 N
Maximum moment applied	14 Nm

3. Sizing the Actuators

The manipulator was modeled with the VPE-PKM system taking into account the current position and acceleration of the center of gravity of each component of the ma-chine. To justify the choice of the extendable arm actuators, the maximum load required and the speed for each of them are calculated. The critical factor in the analysis is always J, here used to calculate the forces required by the motors to balance the external loads ap-plied to the end-effector, but two other important parameters are taken into account: the effect of the weight of the machine (assuming that no other balancing device is used) and the forces of inertia during acceleration [32]. The required speeds, accelerations and ex-ternal forces applied to the end-effector have been defined by the industrial application and summarized in Table 1.

Tsai [33, 34] have shown how the effect of external forces is negligible compared to that of inertial and gravitational loads in each analyzed position. Furthermore, the actuators 2 and 3, of Fig. 1, show a symmetrical behavior, thanks to their spatial arrangement in the plane.

3.1 Analysis of Internal Loads

A Near a singular configuration the forces required in at least one actuator tend to infinity, thus generating high voltages in the mechanical structure. But the load of the actuators does not completely describe the stress state of the entire structure: many components of the external forces and moments applied to the end-effector do not produce any reaction to the actuators (since the machine has less than 6 DOF). Having 3 translational DOF, an applied moment is not balanced by an effort in the actuator, but causes a load in the mechanical structure [35].

For this reason, the J-based analysis does not give any indication on the optimal location of the end-effector and the arm (J depends only on their orientation), although these design parameters are important, because they strongly influence the load on the joints. passive (mainly torsional load on the arms).

It is therefore useful to build an extensive and accurate model of the machine (a similar approach was presented by Patel), by inserting dummy joints in the structure, in order to evaluate the effect of displacement or deformation on the positioning accuracy of the tool. Fictitious joints are characterized by infinitesimal displacements and therefore not involved in direct and inverse kinematics. Starting from the global and differentiated kinematic model, we obtain a relationship between infinitesimal displacements:

$$\delta q_{active} = J\,\delta x + S\,\delta q_{fictitious} \tag{1}$$

where we have:

q_{active} : vector of coordinates of the active joints
x : position vector of the mobile platform
J : Jacobian matrix
S : error amplification matrix

Many analyzes can be carried out starting from Eq. (1):

$\delta q_{fictitious} = 0$ (nominal kinematics).

$\delta q_{fictitious} \neq 0$, $\delta x \neq 0$, Analysis of the influence of internal errors and errors of the actuators on the accuracy of the end-effector.

Analysis of the influence of internal errors and errors of the actuators on the accuracy of the end-effector.

Near a singular configuration, a force applied to the moving platform requires extremely high forces from the actuators to keep the machine locked.

Considering the actuators locked in a non-singular configuration ($\delta q_{active} = 0$), the internal stresses related to the motion of the end-effector can be analyzed with the speeds at the different dummy joints, positioned where the internal stresses must be evaluated:

$$\delta x = J^{-1} S\,\delta q_{fictitious} \tag{2}$$

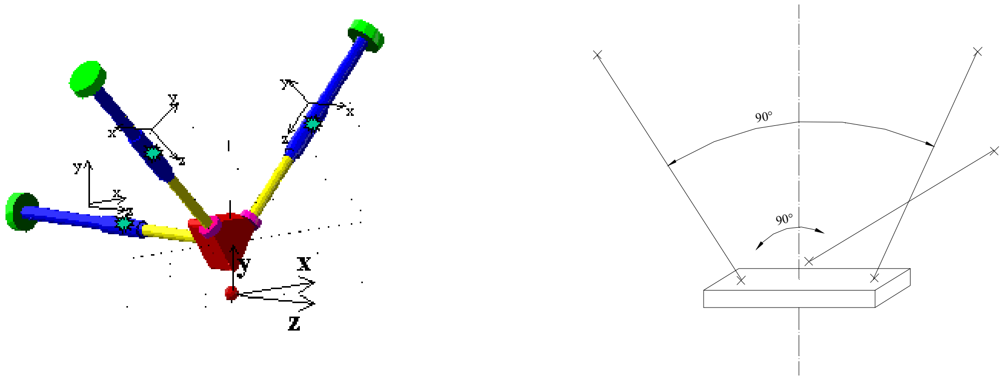

Fig. 1. ADAMS model of the Dragon Fly with the main reference systems on the arms and on the mobile platform.

Table 2. Loads on actuators.

Structure	Maximum loads [N]	Bending X [Nm]	Bending Y [Nm]	Torque Z [Nm]
1	860	150-180	80-120	30-50
2, 3	1200	40-55	90-110	40-60

As expected, many of the internal stresses, measured at the dummy joints, tend to infinity near singular configurations. The evaluation of internal efforts in the critical points of the structure will be used as guidelines for the following analyzes on the flexible model of the structure. Being a kinematic analysis, it is not possible to determine internal tensions in the hyperstatic sections of the machine. For each position the bending and torsional loads on the three arms are evaluated, keeping separate the contributions of gravity, inertial and external. The arm 1 is subjected to a greater flexural load, mainly due to its size and horizontal position. Furthermore, the main contribution to the flexural rate in the arm 1 is mostly due to the weight of the machine, since external forces and moments are not influential.

3.2 Influence of Machining Errors and Machine Confidence

A Based on the duality between kinematics and statics, it is also possible to evaluate the displacement of the end-effector generated by a displacement of one or more dummy coupling, which can be caused by elastic deformations of the mechanical components and/or by machining or assembly errors. These two assessments can be unified when, having the first designs of the mechanical components, it is possible to estimate their stiffness: in this case the Jacobian can be used to calculate how the localized structural compliance affects the overall compliance at the end-effector. By introducing dummy joints to model localized compliance, and applying the PLV, the system equilibrium can be written as:

$$\delta x \cdot F_{end-effector} = \delta q_{\text{fictitious } joint}\ f_{\text{fictitious } joint} \tag{3}$$

The elastic reaction of the fictitious joint is given, through Hooke's law, by:

$$f_{\text{fictitious } joint} = K_{\rho F}\ q_{\text{fictitious } joint} \tag{4}$$

The compliance to the end-effector is related to the infinitesimal movement of the end-effector:

$$x_{end-effector} = C_{EE}\ F_{end-effector} \tag{5}$$

The compliance to the end-effector is related to the infinitesimal movement of the end-effector:

$$C_{EE} = K^{-1}{}_{fl} \tag{6}$$

Finally, Table 2 summarizes the data obtained from the simulations, in terms of maximum load on the actuators, and internal stresses.

4. Control of the Actuators

Studying the kinematics of a mechanical system means facing the problem of singular configurations, where the DOFs of the system change instantaneously. Mathematically speaking, the Jacobian matrices J, which relate the input velocity to the output velocity, are no longer of full rank. For orthogonal machine tools, no singularity is proven where the limiting factor is the mechanical end stop of the joint. As regards the serial manipulator, the Jacobian matrix J expresses not only the relationship between the velocity at the joints and the velocity at the end-effector, but also provides important information on the way in which the forces in the Cartesian representation are plotted against the forces in the joint space. Assuming that k is the axial stiffness of each arm and that all the other components of the machine are perfectly rigid bodies, the equation gives the kinematic stiffness of the manipulator, i.e., the relationship between the force F in the Cartesian representation applied to the end-effector and its x-position. This means that the stiffness values are strongly influenced by the position and orientation of the tool within the work-space.

The requirements that must be met for a PKM are:

- Sufficient control calculation capability to carry out control procedures including bidirectional transformations in the control cycle. As an assumption, all measured values must be available at the same time.
- Open architecture for both hardware and software modules.
- The achievable control quality strongly depends on the time delay between the re-cording of the measured value and the transmission of a new control signal to the actuators. The architectural design should allow for a minimum delay time.

4.1 Errors and Calibration

For the 6-dof PKM, the general position and orientation depend on all of its actuators. A failure in just one actuator can cause an error in position and orientation in all directions. Additionally, multiple joint reversals can occur for some path through the work-space, causing non-linear errors in the tool path.

Usually, the sources of errors in the kinematic model are attributed to uncertainties in theoretically constant parameters such as the coordinates of the joint centers on the base and on the moving platform, the arm lengths at the initial position and in the home position, as well as the position of the axis of the shaft and the length of the tool. Errors are also associated with variable parameters such as arm length, which is affected by localized heat generation in the screw/lead system and joints.

Another problem source of the error is given by the fact that the controller has an imperfect knowledge of the absolute values of the input parameters to the kinematic model (for example, absolute distance between the mates of the centers of the joints on the mobile platform and on the base, on the lengths of the arms in the home position and on thermal distortions of the arms).

Most error analysis methods have essentially been limited to off-line calibration and accuracy analysis. The error analysis, in general, was accomplished through a quasi-static error evaluation based on the manipulator kinematics.

Currently quasi-static error evaluation techniques, based on parallel manipulator kinematics and/or stiffness, are applied to the performance evaluation of a PKM used as a machine tool. However, these methods exclude dynamic terms; thus, limiting their effectiveness for applications where high speeds and accelerations are involved.

4.2 Structural Dynamic Characteristics of Manipulators

Structural characteristics of manipulators include stiffness, inertia, damping, and natural frequencies. In robots, the tensions in the arms are relatively low. The cantilevered movement of the arms develops high inertia forces which lead to high momentum values in the sections close to the joints.

If the stiffness of the arms and joints is inadequate, these forces cause large deflections around the affected sections, especially at the end-effector which is located at the end of the whole chain of arms. Large deflections for a given load are a symptom of low natural frequencies which are undesirable from the point of view of the accuracy and behavior of the manipulator. Since stiffness values change with configuration and loads, inadequate stiffness would lead to reduced robot accuracy. Analyzes show that the importance of structural stiffness increases with higher speeds and accelerations and with the size of the manipulator. Another behavior characteristic of a robot can be improved by increasing the stiffness, increasing the natural frequency and increasing the damping. All this demonstrates a strong relationship between all the structural dynamic characteristics of a manipulator. The greatest weight is given to the stiffness because the inertial characteristics are determined more by the estimated load, while the natural frequencies are characteristics descending from the stiffness and from the inertia.

Stiffness is one of the most important general machinery design criteria. The problem of improving stiffness becomes important when conventional techniques, such as section reinforcement or the use of conventional materials with high modulus, are in many cases unacceptable, either because they are counterproductive (because the increase in weight leads to an increase in inertia forces and large deflections), and because they are expensive. In many cases both the external and internal dimensions of the arms are limited by design or application constraints; the supports must be custom-designed for specific applications, thus causing the robot to lose its universality.

Since the most important goal is the reduction of deflections in the structural chains caused by forces applied at some points, the use of a "compliance" parameter instead of "stiffness" is natural in many cases since "compliance abatement" is equivalent to “deformation abatement”. The actual stiffness and compliance are the result of four basic factors:

1) structural deformations of the elements that transmit the load (beams, rods, slabs, shells).
2) contact deformations between nominally small (spheres) or nominally large sur-faces.
3) deformation in motors and actuators.
4) modification of the numerical values of stiffness due to kinematic transformations between the area where the deformation originates and the point where the effective stiff-ness is analyzed.

Obtaining high stiffness in small structures is positive for the system inertia. The best way to achieve inertia reduction is a judicious choice of materials and/or the shape of the sections.

4.3 PKM

The considered PKM mainly finds application in the traditional robot fields (pick and place), and for high precision positioning. These applications exploit some of the characteristics of parallel kinematic chains, in particular, the lightness of the structures and consequently their low inertia which allows high speeds and accelerations. On the other hand, the high load-bearing-to-weight ratio, coupled with the inherent structural stiffness given by the parallel link, makes the use of a PKM suitable for high precision positioning.

It must guarantee the following performances:

- high load-bearing-to-weight ratio (the payload is carried by several links in parallel);
- non-cumulative joint error;
- high structural stiffness (the load is held by the parallel connections and in some structures the stresses are limited to those of tension-compression);
- modularity (each kinematic chain is made up of the same physical modules);
- positioning of the motors near the fixed base;
- simpler solution to the inverse kinematics problem.

5. Dragon Fly Prototype Project

The previously analyzes (sizing of the actuator and internal analysis of the loads) were used to correctly dimension the actuators of the PKM Dragon Fly. The final layout of the Dragon Fly prototype is shown in Figs. 2, 3. The base is composed by two different units, the upper one, with the housings for the universal joints, common to the two robots, while the lower module depends on the application. In the following, some details about the project are given in particular on the mechanical elements, by highlighting the crucial points [36, 37].

5.1 First Design of the Arms

The arms have been sized considering the worst stress states, where the bending effects are significant. The telescopic system of the recirculating ball screw adopted for the three arms is the same, albeit with a different stroke (350 mm for the two vertical arms and 500 mm for the horizontal one).

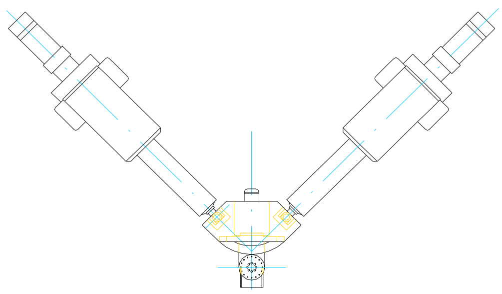

Fig. 2. Front view of the Dragon Fly mechanism.

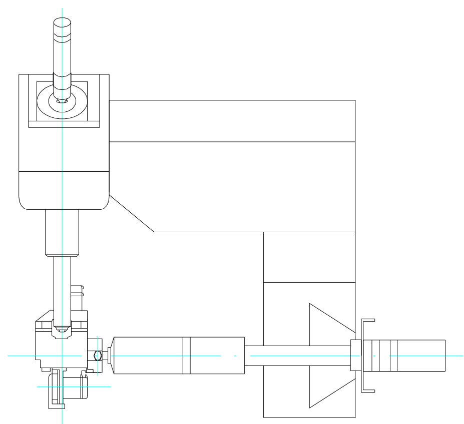

Fig. 3. Lateral view of the Dragon Fly mechanism.

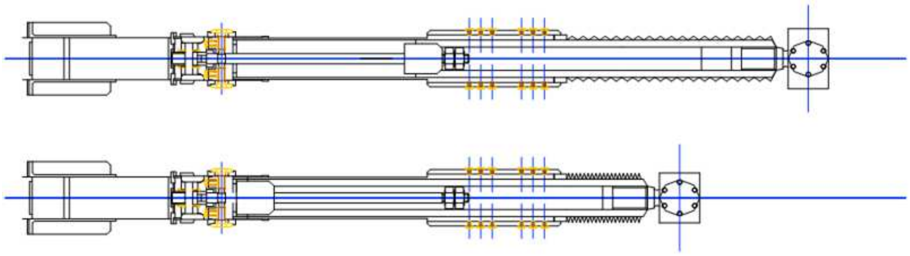

Fig. 4. Longitudinal section of an arm.

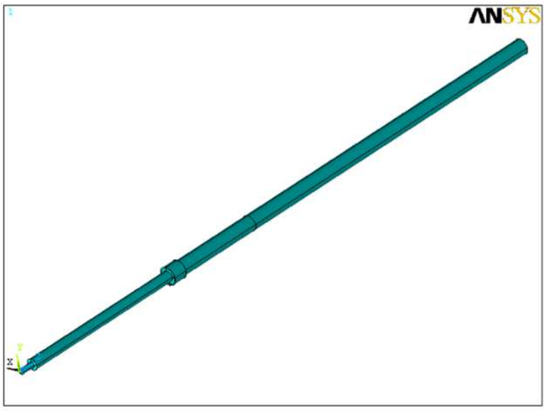

Fig. 5. FEM model.

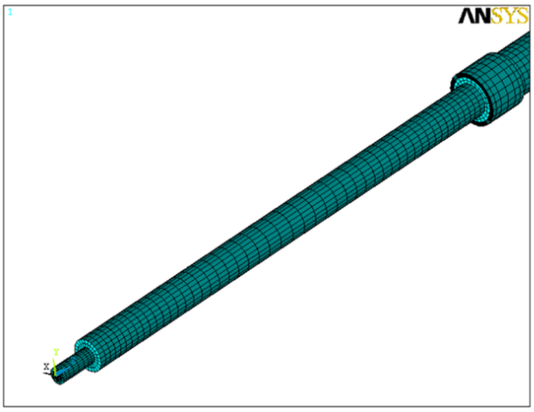

Fig. 6. A zoom on the relative modeling of the elements.

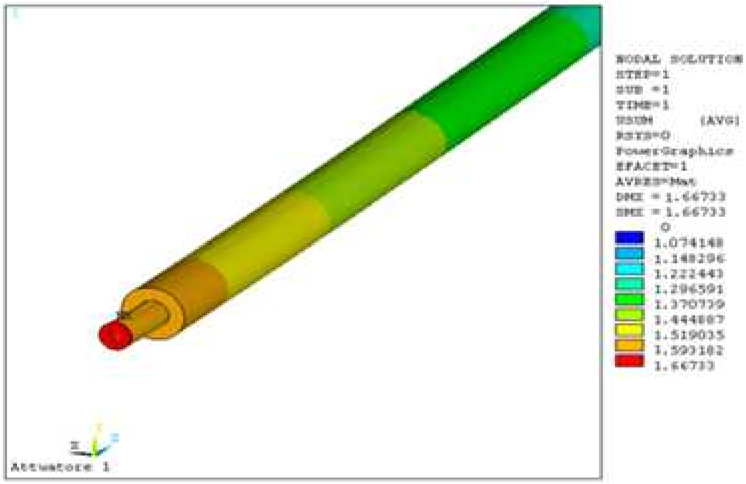

Fig. 7. Results obtained with the considered model.

Figure 4 shows the longitudinal section of the arm, relative to the maximum and minimum stroke. The design of the sliding coupling was done very carefully, to ensure a pure linear relative motion between the external cylindrical covers and the mobile one connected to the screw, under the hypothesis of heavier internal load states.

5.2 FEM Analysis

Figure 5 shows the FEM model of the actuator, consisting of three coaxial cylinders: the recirculating screw and its housing and the ball sleeve.

A zoom on the relative modeling of the elements is shown in Fig. 6.

An average steel was chosen as material, with an elastic modulus E = 2.1×105 MPa, specific weight γ = 7.8 ×103 kg/m^3 and ratio E/γ = 2.7×107 m^2/s^2.

The heaviest machining conditions were taken into consideration: maximum extension of the actuator and maximum bending moment; the ranges of values to be obtained have been set:

- Accuracy: +/- 0.5mm;
- External loads: a maximum of 70 N for the force applied to the tool end in the X-Y plane during machining, plus dynamic loads;
- Maximum speed of the end-effector: 1 ms^{-1};
- Maximum acceleration of the end-effector: 5 ms^{-2}.

The obtained results are shown in Fig. 7. By sizing the actuators according to the most severe conditions, the structures were very slender, with evident lack of stiffness, as shown in fig. 8, which resulted in positioning errors equal to approximately 3 times the allowed value. Obviously, the highest values of displacement were obtained at the tip, so the part that was subjected to a stronger stiffening was the latter, which from the initial 6 and 10 mm (respectively for the horizontal and the two vertical actuators) has been increased to diameters of 10 and 14 mm, while all other diameters have been increased to a lesser extent as the opposite end of the actuator was reached.

This constructive solution was obtained by modeling each actuator at Ansys, arriving at an acceptable solution to the problem (Figs. 8, 9):

- Total displacement of the actuator 1 = 0.39 mm.
- Total displacement of actuator 2 = 0.095 mm.

Finally, Fig. 11 shows the final project of the Dragon Fly actuators.

A not too fine mesh was generated with an average size of 2 mm because the geometries are not complex and the elements are of the solid tetrahedra type with 4 nodes.

As for the rotations, they range from 9 (for actuators 2 and 3) to 20 mrad (for actuator 1) (Fig. 10).

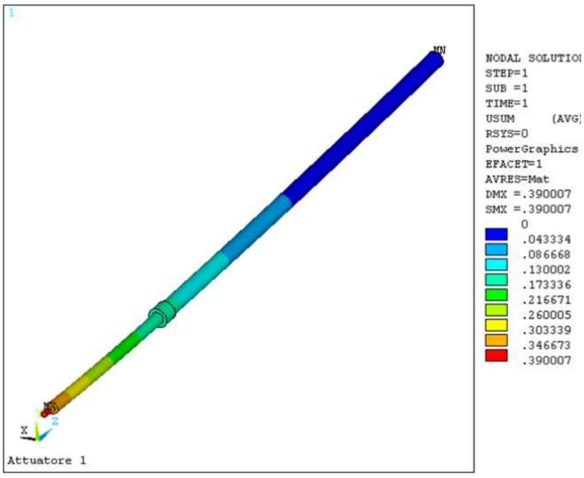

Fig. 8. Deformed actuator 1.

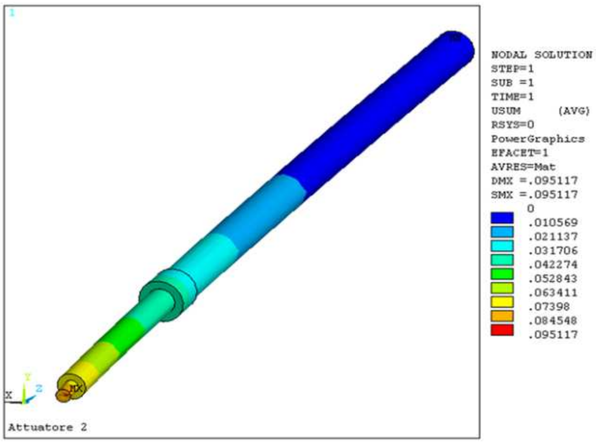

Fig. 9. Deformed actuator 2.

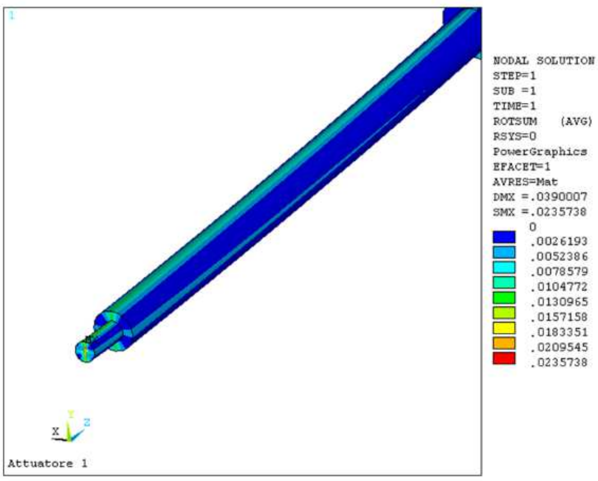

Fig. 10. Resulting rotations on the actuator 1.

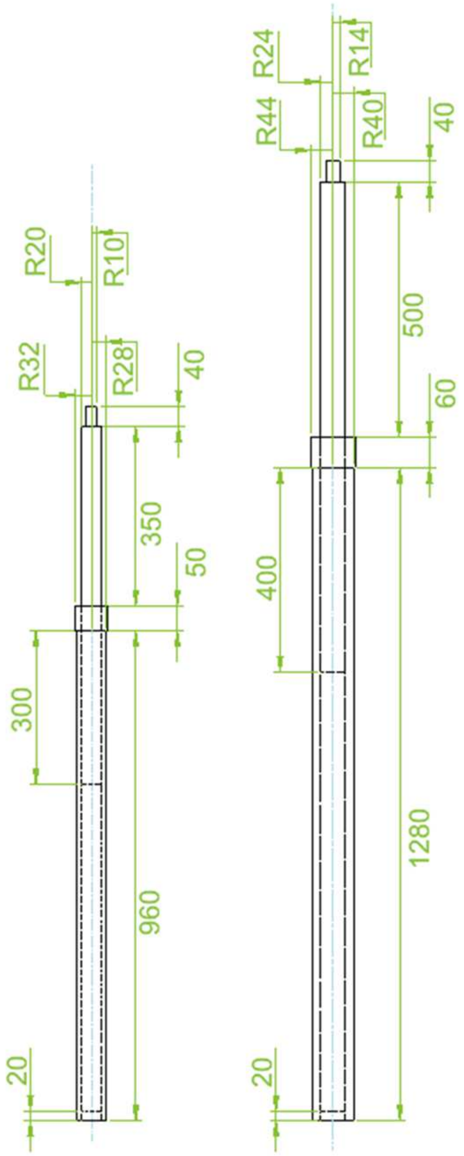

Fig. 11. Final sizing of the actuators.

5.3 Calibration Strategy

PKMs are considered more accurate compared to the influence of error on serial ma-chines. On the other hand, it is well known that the error of an axis leads to an error in the position and orientation of the end-effector. Thus, it is obvious that the outcome of the precision of a PKM can only be successfully addressed if all the sources of error are included. The global approach to increasing accuracy consists of the following 3 steps:

1) Evaluation of sources of error: this means evaluating and predicting the magnitude of individual errors, and if possible, their influence on the accuracy of the PKM. Three main sources of errors must be considered: kinematic errors (due to machining and assembly errors in the joints and arms), errors due to the force of gravity and errors due to thermal loads. The end-effector error due to the previous two sources of error can be easily predicted; on the contrary, thermal expansion is highly dependent on environ-mental conditions. Therefore, such a situation should be avoided as much as possible by a design of a particular mechanism, or by a direct measurement system.
2) Development of an extended kinematic model, which takes into account the current geometric parameters. For the Tsai platform the number of unknown parameters is 21 (location of the joints and current length of the arms). To operate the identification of the parameters, a function must be defined that maps the kinematic parameters relating to the error between the predicted and measured positions. Two strategies can be found in the literature to measure the position of the end-effector: a direct measurement of the position of the end-effector, or an indirect calibration using a passive arm, the length of which is known. The latter will be chosen. The error function can be written in different ways. Another flexible formulation for the residual error is the comparison between the direct kinematics problem with the length of the redundant arm. The kinematic parameters can be evaluated by minimizing the residual error for m different positions using non-linear optimization strategies. A set of measurements with at least m = 28 different positions is needed to identify the 28 kinematic parameters of the mechanism.
3) Implementation of the extended kinematic model in the controller to compensate for those errors that can be easily predicted (gravity and machining and assembly loads). The very first results show that the PKM has a good repeatability on positioning (of the order of 50 m), but a complete characterization of the machine is underestimated. Then, a calibration strategy that takes into account unavoidable machining errors can be developed and integrated into the control system.

6. Conclusions

It is evident, as we have seen, that a better understanding of the real advantages offered by PKMs compared to traditional serial devices is necessary. In fact, the advantages and disadvantages of these two categories of machine tools have been highlighted, which can vary from the reduction in the number of devices and adjustments required to ma-chine complex parts in order to undoubtedly obtain a better surface quality, at the expense of greater complexity in control, error compensation and costs.

After a short analysis of the conditions that have allowed recent advances in systematic design, kinematics, dynamics, error analysis, calibration and control, the reasons why the researchers' expectations on the engineering of such products have been partially dis-regarded. This involved an in-depth study of the optimization criteria previously introduced in the conceptual design of two architectures, the 3 DOF Tsai mechanism and the Hexapod 6 DOF, describing the industrial requirements and showing the layout of the two types.

For these reasons, a particular aspect of the Dragon Fly prototype project was examined in detail, and then additional studies were carried out on the evaluation of the loads applied to the actuators in operation. In fact, both external and inertial forces were taken into account, in addition to internal loads, for the purpose of evaluating the influence of the compliance of the arms on that of the end-effector. This analysis demonstrated the lack that the current arms show regarding the stiffness necessary to meet the initial design requirements.

Moreover, a careful structural analysis of the stiffness of the actuators was carried out with an FEM technique, aimed at identifying the design methodology necessary to identify the mechanical elements to be stiffened. Subsequently, as an example, the project of the actuators was presented, with the aim of proposing an indirect calibration strategy.

It was therefore possible to show that the performance of the Dragon Fly prototype can be improved by developing and including in the control system a module to compensate for foreseeable errors.

However, the effect of thermal expansion remains to be assessed in this control sys-tem, which can possibly be corrected by introducing a linear measuring device.

The future development of the theoretical optimization studies must therefore:

1. Consider more accurately the dynamic behavior of the mechanism, establishing more correct dynamic indices.
2. Guarantee the generality of the model, also extending it to mechanisms with drive principles not based on extensible arms.

Author Contributions

All authors equally contributed to carrying out the research, whose results are reported in this work. All authors have read and agreed to the published version of the manuscript.

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Conflict of Interest

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Data Availability Statements

The datasets generated and/or analyzed during the current study are available from the corresponding author on reasonable request.

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