Application-Oriented Development of Parallel Kinematic Manipulators with Large Workspace

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Abstract

This paper deals with the potential of using large workspace PKM structures to compete with the manipulation methods used in industry today. Different kinematic solutions are described in relation to application requirements and the PKM potential is illustrated in a specific application, the assembly of aerospace components . For this application a new large workspace PKM concept is under development at the University of Queensland and the design of this PKM as well as of a flexible manufacturing cell using the PKM will be presented.

1. Introduction

The Delta structure [1] has proved that a parallel kinematic manipulator is able to compete with serial articulated robots in specific applications where the disadvantage of the bigger PKM footprint in relation to its workspace is compensated for by the much lower robot arm inertia. With PKM structures having a larger workspace than the Delta robot in relation to the footprint [2, 3, 4] the industrial benefits with PKM solutions should increase. However, it is not easy to challenge the mature robot- and manipulator technology used today. There are in principle 5 different manipulation solutions in industry today according to Figure 1 and it is necessary to find the best profile of PKM features to take up the competition with these 5 existing manipulation solutions. To compete with manual work (1) the strength of PKM technology is not found in increased flexibility but in the potential of better performance and the potential to make bad working conditions obsolete. However, to make this possible the PKM solutions must be flexible enough not to add too big cost for installation, calibration, programming etc. When competing with industrial robots (2, 3) it can be shown that there are many opportunities with respect to performance, flexibility and cost. In the PKM competition with linear manipulators (4), which are used both in high performance applications and in applications with the need of large work space, the low inertia properties will of course be a competitive edge, but simultaneously it is very difficult to obtain the same accuracy and stiffness as in serial linear manipulators using high precision and high stiffness linear bearings. However, a lightweight mechanically not redundant arm system can make the PKM very competitive with respect to flexibility and cost. Finally, there are also possibilities to compete with special customized mechanisms and in this case it is of course the flexibility that could make PKM worthwhile in the applications. It should also be mentioned that completely new applications may come up, where a PKM solution does not need to compete with any existing solution.

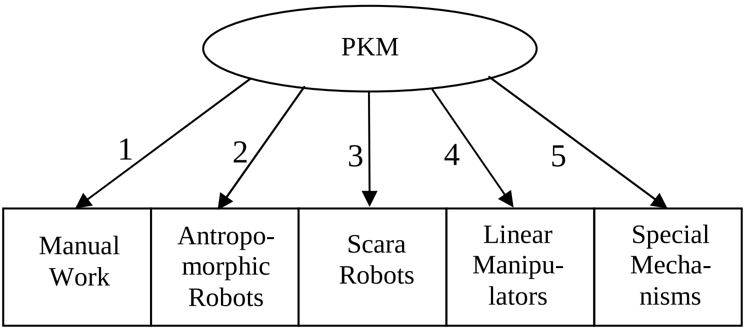

Figure 1:The challange for the PKM development is to find applications in which the PKM technology can compete with the 5 main manipulation solutions used today.

In this paper the importance of finding the competitive edge when making an application-oriented PKM design will be exemplified with a specific application, assembly of aerospace components. Before presenting PKM solutions for this application, a more general presentation will be made of kinematic design issues needed to be considered to build competitive large workspace PKM structures.

2. Kinematic Considerations for the Design of an articulated PKM

Very important when taking up the competition with the manipulation methods used today is not only to obtain as large PKM workspace as possible but also to get a motion pattern that suits the targeted application. For example, Figure 2 shows the kinematics of a PKM with a Scara type of workspace [2], which can easily be adapted to applications in which the tool works mainly in the negative z-direction.

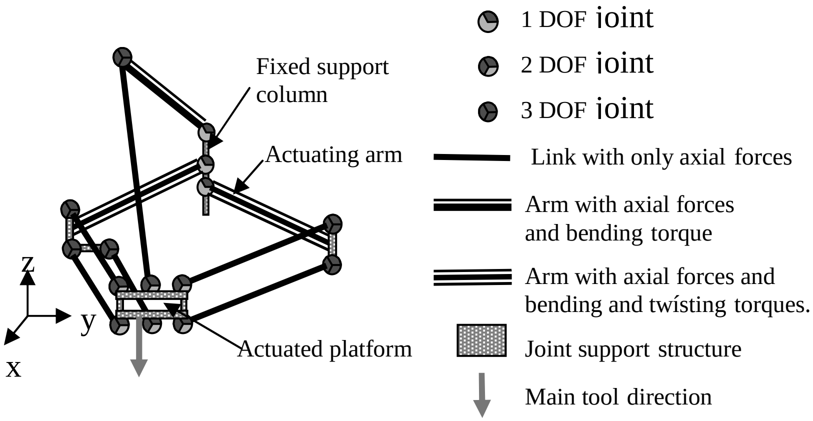

Figure 2: Kinematic Model of an articulated PKM with Scara motion characteristics.

The 2 lower actuating arms rotate in a horizontal plane around the fixed central support column and the upper actuating arm is responsible for the vertical movements of the actuated platform. The links between the 2 lower actuated arms and the actuated platform are clustered with 3 parallel links to the left arm and 2 parallel links to the right arm. With this configuration of the links the actuated platform will always be vertical (parallel with the z-axis) but the platform will rotate as much as the left actuating arm around the z-axis when it is moved in the workspace. If the tools for the applications are working only in the negative z-direction as indicated in Figure 2, the rotation of the platform will usually not give any problems. Either the process is not sensitive to this rotation at all as for laser cutting and drilling in the negative z-direction or the rotation will anyhow be compensated for by a forth axis parallel with the z-axis as for pick&place and palletizing. However, if the tool must work in parallel with the xy-plane, for example in such applications as measurements, machine tending, material handling, assembly and grinding, the accessibility and work space could sometimes be reduced because of the platform rotation. If this problem is not acceptable, the link configuration shown in Figure 3 should be used instead. The rotation of the actuated platform with this configuration will now be smaller than in Figure 3 since it will just depend on the angle of the 3 link cluster relative the x-axis.

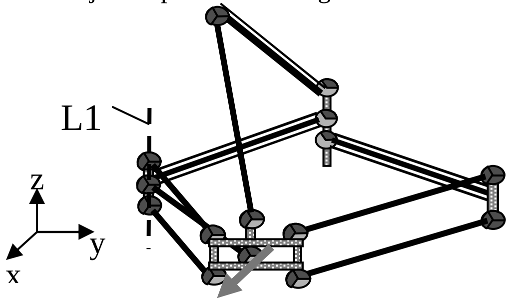

Figure 3: Kinematic Model of an articulated PKM with smaller platform rotation around the z-axis than in the implementation of Figure 2.

The only difference between the link configuration in Figure 3 and Figure 2 is that the joints for the 3 links on the left actuating arm are now mounted along a line L1 instead of being mounted in the triangular pattern necessary to have all the 3 links in parallel.

The parallelograms used in the Scara types of PKM in Figures 2 and 3 will give the PKM limited workspace in the z-direction. This will reduce the generic use of a PKM in applications like painting, material handling and assembly, in which it is sometimes necessary that the robot is able to work upwards as well as downwards in the same installation. Figure 4 shows how this limitation can be handled by completely replacing the parallelograms with triangular link structures in such a way that a horizontal axis of rotation L2 is obtained.

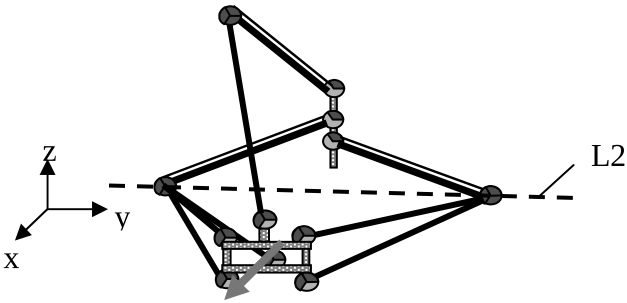

Figure 4: Kinematic Model of articulated PKM with link configuration for increased workspace in z-direction.

The PKM in Figure 4 [3] can easily move its manipulated platform to point both upwards and downwards. Actually, the structure can also work in its backward direction. The workspace in the backward direction will be limited by collision between the upper arm and the central support column of the PKM. With a telescopic design of the upper actuating arm it will however be possible to reconfigure the upper arm to work from above when the robot structure is in its backwards configuration and then the work space in the backward configuration will be almost the same as in the forward configuration. Of course, the robot could as well move into the backward direction by rotating the actuating arms around the center of the PKM, but when working in the upper part of the workspace it will be much faster to move to a backward position directly than to rotate the whole robot structure. This is important if the PKM is hanging up and down and is used for continuous processes for which speed reductions are not tolerated, as in painting, gluing and welding.

3. Kinematic Considerations for the Design of a linear PKM

The reconfiguration between forward and backward manipulation as can be performed with the structure in Figure 4 does not add any workspace for the articulated type of PKM.

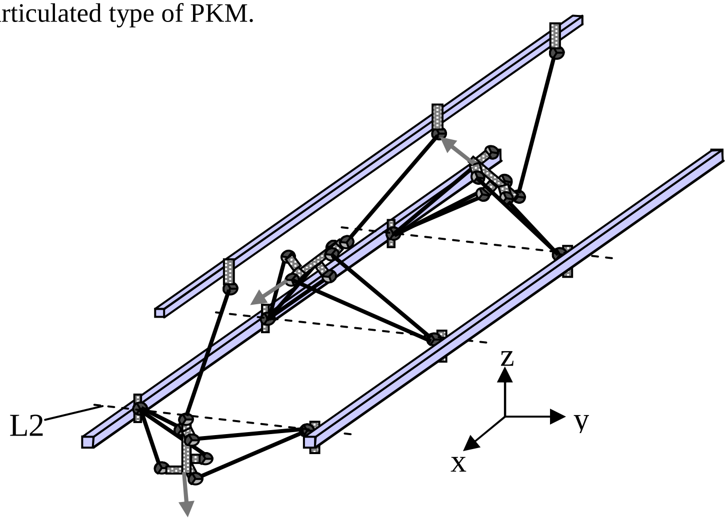

Figure 5: Changing the configuration from forward to backward manipulation when the link structure in Figure 5 is connected to linear actuators instead of actuating arms.

However, when a PKM with linear actuation is used [4, 5], the backward configuration at the end of the linear tracks cannot be reached without reconfiguration. If the same reconfiguration principle as in Figure 4 is used for a linear PKM, the situation as found in Figure 5 will be found. The upper linear actuator will rotate the link structure around the axis line L2 until a singularity is reached. This singularity, which does not give any problems in the articulated PKM in Figure 5, can be passed by means of gravity, but the tool will now point upwards, a direction, which in most cases is not useful for a linear manipulator of gantry type. Instead a reconfiguration principle is needed to go between 2 configurations with the tool pointing downwards as shown in Figure 6.

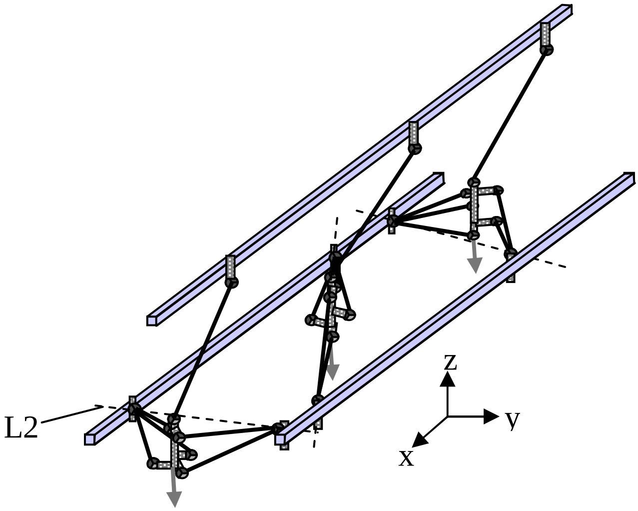

Figure 6: Alternative reconfiguration concept as compared to Figure 5. In this case the tool attitude will be the same after the reconfiguration.

In order to go from a forward to a backward configuration according to Figure 6, the singularity (where the line L2 goes through the center of the platform) must be passed. In the singularity the platform will gain 1 DOF and to compensate for this, one joint can be switched from 3 DOF to 2 DOF, for example by means of a mechanical brake connected to a bearing in the joint. Both the stiffness and the accuracy of the PKM will be reduced when the singularity is passed and therefore this should be made without running an accurate process. This means that the forward and backward configurations could be seen more or less as 2 different manipulators. Thus, instead of making a linear actuated PKM with the reconfiguration capability it could also be possible to mount 2 different link structures on the same linear actuators with one mounted in forward and the other mounted in backward configuration. However, for cost reason the reconfiguration concept will most likely be the best option, if a multi-robot solution is not needed to increase the productivity.

In most applications a serial gantry robot works with constant tilt angles and to obtain this feature the link structure of Figure 2 [4, 5] or Figure 3 can be mounted on the linear tracks. Using the link structure in Figure 3 the same reconfiguration from a forward to a backward workspace can be made as in Figure 6, but the platform will in this case always maintain a constant tilt angle. Both in this case and in the case of Figure 6 the upper link will work from the other side of the platform after the reconfiguration. To obtain the same workspace in the backward configuration as in the forward configuration the upper link must be manipulated to the other side of the platform. The problem then is that the platform will be manipulated deep down into the workspace, where a work object could reside. To avoid this problem the upper link could be telescopic and if this new telescopic linear DOF is passive the gained DOF can be compensated for by locking 1 DOF in a 3 DOF joint.

In some cases, for such applications as palletizing, pick&place and assembly, only 3 DOF gantries are needed. Then beside the tilt angles also the platform orientation must be kept constant. To make this possible the link configuration of Figure 2 can be mounted on the linear tracks [4, 5]. However, then the internal singularity of the parallelogram working in the horizontal plane will reduce the work space in the backward configuration. To obtain a full work space in both directions the triangular joint configuration for the 3 link cluster at the linear actuator side (compare Figure 2) must be rotated around an axis parallel with the z-axis, for example by means of a motor-driven joint mounting structure. This means that the platform will have one constant orientation in the forward workspace and another constant orientation in the backward workspace.

4. Application of a linear PKM for the Assembly of Aerospace Components.

With the reconfiguration shown in Figure 6 it will be possible to obtain a total workspace larger than that for a serial gantry robot having the same footprint. Thus, there will be a good opportunity to compete with serial Cartesian manipulators, especially in applications where big and very expensive manipulators are used today. One such example is found for the manufacturing of aerospace components such as flaps and wing sections. Thus, a prototype is under development at the University of Queensland (UQ) for drilling, deburring and riveting of airplane components mounted in vertical jigs. Since the jigs are vertical the triangular constellation of the 3 linear actuators according to figures 5 and 6 is rotated 90 degrees around the x-axis. The manipulator prototype with its defined coordinate axes can be seen in Figure 7. In this type of application the work objects are quite flat and it is an advantage to have a constant platform tilt angle and therefore the link structure in Figure 2 has been connected to the linear actuators.

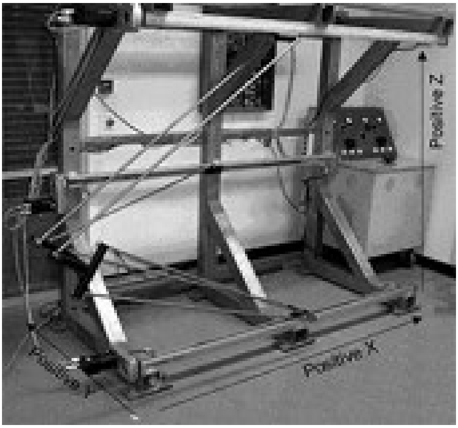

Figure 7: PKM prototype for aerospace application at the University of Queensland (UQ).

The implementation of the link structure in Figure 7 is just used for the test of the controller and during 2005 the links and joints designed for the application requirements will be mounted on the linear actuator modules.

4.1 Stiffness Analysis of the Link Structure.
For the dimensioning of the links and joints to be used in the application, a stiffness analysis has been performed with the following assumptions:

1. Elastic effects in the motor gearboxes and the lead-screws can be compensated for by using linear optical encoders and stiff position control loops. Hence, these effects are not taken into account in the analysis.
2. Initially the stiffness of the support framework for the linear actuators is ignored. The support stiffness is analysed separately in section 4.2.

3. A stiffness of 250 N/μm is assumed for the joints. Such joints are available commercially.
4. When carbon epoxy tubes are used for the Tau links, a stiffness of 480 N/μm and 640N/μm for 1.5 metre and 2.0 metre links, respectively, can be achieved.
5. The combined stiffness of a 1.5 metre and a 2.0 metre link with two universal joints with stiffness 250N/μm at either end, is 99N/μm and 105N/μm, respectively.

Hooke's law, $F/A = E * \varepsilon$ is used to calculate the stiffness of the carbon epoxy tubes. F and A are the axial force acting on the link and the cross sectional area, respectively. E is the Young's modulus and ε is the strain $(L_2-L_1)/L_1$ where L_1 is the link length when F=0 and L_2 is the link length when a force F is applied. The Young's modulus for carbon epoxy is 120GPa and we choose tubes with a cross-sectional area of 0.008 m^2. For a 2.0 metre link, we have $L_1 = 2.0$ and we assume a 1.0 μm compression, ie. $L_2 = L_1 - 10^{-6}$, hence $\varepsilon = -5*10^{-7}$. The force required to compress the link by 1.0 μm equals $F = A*E*\varepsilon = 480$ N. Similarly, the stiffness of a 1.5 metre carbon epoxy tube with the same cross-sectional area is found to be 640 N/μm.

When mounting two universal joints, each with a stiffness of 250 N/μm, at either end of the carbon epoxy tube, the combined stiffness is 99 N/μm for a 2.0m link and 105 N/μm for a 1.5m link. With these stiffness values established, we propose the following stiffness analysis approach of the Tau link structure:

1. Apply a unit force/torque $\mathbf{F}_j$ sequentially in all the Cartesian directions at the tool centre point (TCP).
2. Calculate the corresponding link forces.
3. By using the link forces and stiffness values above, compute the corresponding axial link deflections.
4. Compute the Cartesian position and orientation error vector $\Delta\mathbf{X}$ from the new link lengths and the forward kinematics.
5. All raw elements for each column in the compliance matrix can be calculated as $S_{ij} = \Delta\mathbf{X}_i / \mathbf{F}_j$ for each unit force/torque.
6. The Cartesian stiffness matrix equals $\mathbf{K} = \mathbf{S}^{-1}$.

The entire compliance matrix **S** (6x6) of the Tau structure can be calculated in this way, ie.

$\Delta\mathbf{X} = \mathbf{SF}$ where

$$\Delta\mathbf{X} = \begin{pmatrix}\Delta X & \Delta Y & \Delta Z & \Delta\theta_X & \Delta\theta_Y & \Delta\theta_Z\end{pmatrix}^T ,$$

$$\mathbf{F} = \begin{pmatrix}F_X & F_Y & F_Z & M_X & M_Y & M_Z\end{pmatrix}^T$$

F_x, F_y, F_z, M_x, M_y and M_z are external forces and torques at the TCP. The analysis above is much faster and simpler than a FEM simulation. In the method above, we have exploited the fact that the external forces and torques cause no bending moments in the links. The external forces cause either a pure compression or an expansion of each link and joint.

The results of the analysis approach are shown in Figure 8 for K_x, in Figure 9 for K_y and in Figure 10 for K_z. All the stiffness values have been calculated as functions of the Y and Z positions of the TCP. When the PKM moves in the X-direction, the entire link structure is translated with no changes in the parallelograms. Hence, the stiffness maps in Figure 8, Figure 9 and Figure 10 are independent of TCP position in the X direction. Note that the figures only show the translational and not the rotational stiffness values.

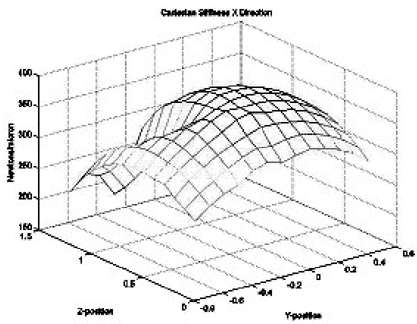

Figure 8: Cartesian stiffness X-direction

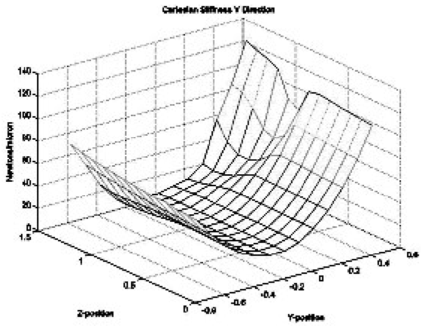

Figure 9: Cartesian stiffness in Y-direction

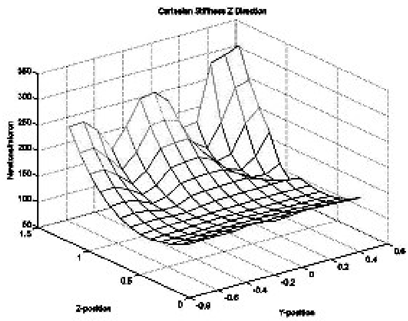

Figure 10: Cartesian stiffness in Z-direction

The stiffness values in the X and Z directions are extremely good, ie. above 200N/µm for X and above 100N/µm for Z in the entire workspace. The stiffness in the Y direction is lower, but also reasonably high – the worst case stiffness is approximately 11 N/µm in the Y-direction while the best case is 127N/µm. The reason for the lower stiffness in the Y-direction, can be seen from Figure 7. The single arm will support most of the forces in the Y direction and to obtain a higher stiffness in this direction the single arm can be given a stiffer design.

4.2 Stiffness Analysis of the Actuator Support Structure.

The analysis in the previous section presented the stiffness of the link structure. In this section the stiffness analysis of the support framework shown in Figure 7 is presented. The analysis was performed with a FEM software tool [6]. Two different configurations of the support framework were analysed.

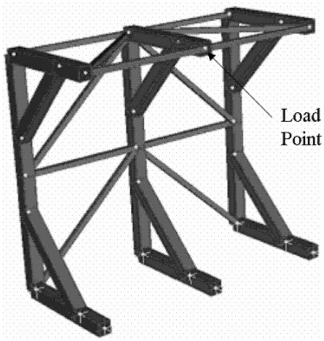

Figure 11: Support Framework for the PKM prototype at UQ

The first support framework is illustrated in Figure 11 and the stiffness values (F / Δ) at the load point are as follows (units in Newtons per micrometer – N / μm):

x-direction	$F_z / \Delta_x = 2.21$	$F_x / \Delta_x = 2.13$
z-direction	$F_z / \Delta_z = 1.76$	$F_x / \Delta_z = 2.21$

Table 1: Stiffness Matrix for Support Framework 1

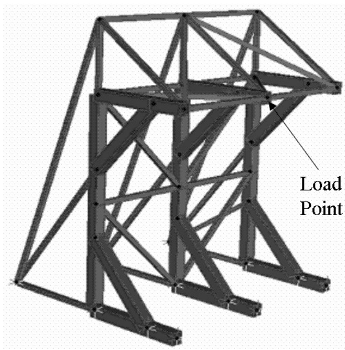

Figure 12: Extended Support Framework

The second support framework is illustrated in Figure 12 and the stiffness values (F / Δ) at the load point are as follows (N / μm):

x-direction	$F_z / \Delta_x = 58.48$	$F_x / \Delta_x = 29.15$
z-direction	$F_z / \Delta_z = 13.55$	$F_x / \Delta_z = 63.29$

Table 2: Stiffness Matrix for extended Support Framework.

Square steel sections with dimensions 100x100mm and thickness of 4mm were chosen for the main beams in Figures 7, 11 and 12. The dimensions 40x40mm and thickness of 4mm were chosen for the back and top support beams. Verified stiffness measurements on the UQ prototype are shown in Figure 13. The dotted points in the figure show measured deflection vs. measured forces. The applied force was applied in the vertical direction at the load point of Figure 11. The straight line in Figure 13 is a least-squares fit to the measurements. The stiffness coefficient of the least-squares fit was found to be 1.33 N/μm which is 25% lower than the FEM analysis result for F_z / Δ_z of Table 1. The lower stiffness of the prototype vs. the FEM analysis could be explained by additional compliance in welds, bolts and floor mounting that were ignored by the FEM analysis. To match the stiffness of the link structure a support framework as in Figure 12 should be used. This framework will have a weight of 349kg, which is low compared to the weight of a conventional serial-type manipulator with the same work space. Further weight reductions can be achieved by designing a carbon fibre support framework.

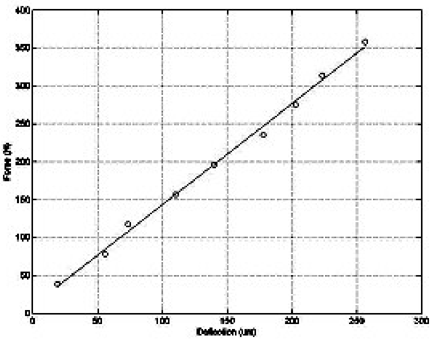

Figure 13: Support Framework Stiffness Measurements

4.3 Manufacturing Cell Design.

When designing a manufacturing cell with a new manipulator concept the combined stiffness and accuracy of both the support framework, the link structure, the wrist, the tool and the jig must be taken into consideration. For example, it was shown that the stiffness (Table 1) of the stand-alone support framework in Figure 11 did not match the stiffness of the link structure (Figures 8-10). One possibility to get around this problem without building the more complex support framework in Figure 12 is to introduce clamping mechanisms that give stiff docking bridges between the support framework and the jig. This will drastically decrease the stiffness requirements on both the jig and the manipulator support framework. Beside using this idea directly for the structure in Figure 7 it can also be used for an even more flexible manipulator according to Figure 14. In this case the linear actuators are vertical and the support framework is mounted on a base, which can be moved around on the floor. When a manipulator is needed in the work shop it is moved to the manufacturing site, docked to the jig and then a calibration program is run to probe calibration points on the jig. In this way both high stiffness and high accuracy can be obtained with a low weight very flexible manipulator. Figure 15 illustrates this scenario for a flexible manufacturing cell that can be used for example for drilling in carbon epoxy aerospace components. Because of problems with compliant work object structures a second manipulator is used to generate counter force during the drilling. To work on objects that are longer than the width of the manipulator (in the y-direction) the manipulators can simply be moved and docked to different parts of the jig. This could either be made manually or using a track motion, on which the manipulator is mounted. For tool exchange a tool holder can be mounted above the manipulator, whereby the upper triangular part of the workspace in the YZ-plane (see Figure 14) can be used.

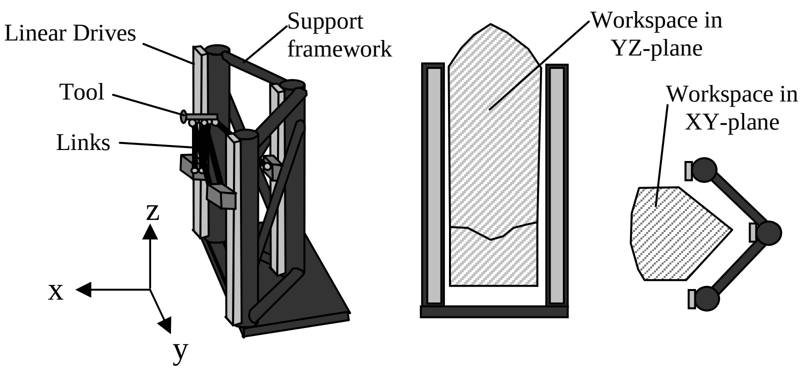

Figure 14: Example of flexible PKM design for aerospace applications.

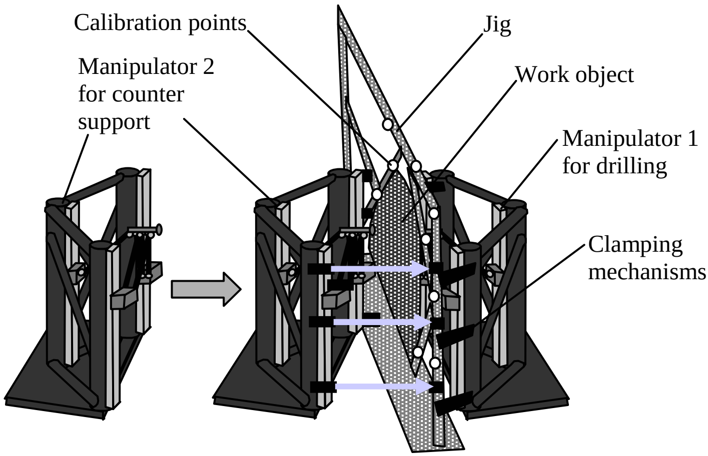

Figure 15: Example of manufacturing cell for the PKM in Figure 14.

5. Conclusions

Summing up, there are many opportunities finding competitive large work space PKM solutions for different applications. What is especially interesting in this respect is that the large workspace PKM structures as exemplified in Figures 2 – 7 and Figure 14 can easily be built up from simple modules, even making it possible to change the kinematic properties in an already installed manipulator to match new application requirements. The specific design for the aerospace application according to section 4 has given the experience that it will be possible to obtain the following large workspace PKM performance benefits:

- low weight
- high stiffness
- high mechanical bandwidth (important for high material removal rate with respect to the chattering problem and for force control for assembly applications)
- high accuracy
- low temperature sensitivity when using carbon fiber material
- high acceleration
- high maximum velocity
- can support large tool forces

These properties make it possible to design a flexible automation system with the following properties:

- simple modularization
- simple installation and reconfiguration (the arms are easily assembled due to low weight and no mechanical assembly redundancy)
- lightweight and cheap manipulator structures
- lightweight, low power and cheap actuators without moving cables
- lightweight jigs and fixtures
- low inertia moving structure that reduces the risk of hazardous impacts
- handles very large work objects, in particular large 2D objects
- simple, fast and very flexible installation
- the manipulator itself requires a low volume relative to the workspace
- fast calibration
- high process velocities (for example with drilling and milling)
- possibility for manipulator-controlled orbital drilling (large accelerations)
- low requirements on constant ambient temperatures (in particular when building support frames with carbon fiber materials)

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