IMPROVEMENT AND OPTIMIZATION OF A RECONFIGURABLE PARALLEL KINEMATIC MACHINE

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ABSTRACT

This paper deals with the development, and the subsequent improvement and optimization, of a parallel kinematics reconfigurable machine. This machine is made of few standard modules, which can be quickly and reliably arranged and rearranged; moreover, this machine represents an attempt to join the advantages of Reconfigurable Machine Tools (RMT) [1] with that of Parallel Kinematics Machine (PKM). The conceived parallel architecture can be assembled either in a planar or spatial configuration (up to six plus one redundant d.o.f.).

KEYWORDS

Reconfigurability, Parallel Kinematics Machine, Modular Machine, Optimum Design, Fast Pick & Place.

INTRODUCTION

Advanced machinery and production system industry plays a very important role in Europe. Actually it's the third industry in terms of added value and has a turnover second only to car industry, and much higher than aerospace. It contributes to keep and to generate new jobs, and moreover it's a source to generate services and, hence, jobs. Advanced machinery and production system industry employs, in small and medium size enterprises, skilled knowledge workers whose number is comparable to that of automotive industry. This industry, in the next years, has to face up to a changing and unpredictable manufacturing environment due to changes in society requirements, in market demand, in enabling technologies and in environment compatibility. In such a context there is the need to have production plants in which it will be possible to rapidly upgrade the whole system according to the changed production and to include new technologies features and new functions. This calls for reconfigurable manufacturing system and reconfigurable machine tools, which allows to adapt the production system to different kind of products.

MACHINE STRUCTURE

The machine concept presented in this paper is based on modular struts (illustrated in Fig. 1), which can be attached or removed according to the required d.o.f. or the whole stiffness.
This machine can be assembled in a planar or spatial configuration using the same standard components.

Fig. 1 – A Modular Strut

The planar machine has two translational d.o.f. and an optional rotation; the spatial machine has three basic translations in space and optionally there is the possibility to add up to three rotations around the main X, Y, Z axes to get a six dof robot. The basic spatial configuration can be easily identified in a 3 P-U-U mechanism similar to a modified linear-Delta [2].

Fig. 2 – The planar Machine

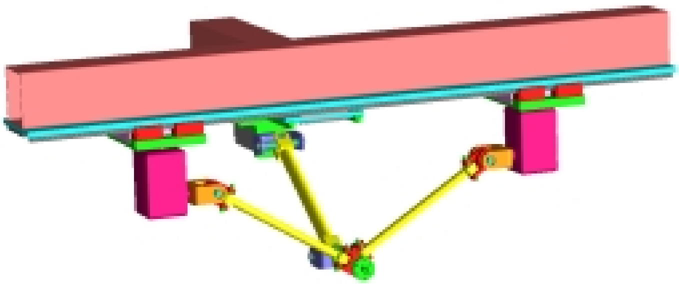

Fig. 3 – The spatial Machine

MAIN ADVANTAGES

The main advantages of this PK architecture are:

1. Modular and reconfigurable structure with the possibility of a different number of d.o.f (up to 6 plus 1 redundant dof). Furthermore, the workspace of the machine can be easily modified: to enlarge the workspace in a given direction it's enough to resize the stroke of one of the linear actuators, since each translational d.o.f. depends only on the linear actuators' stroke (and there aren't RTCP problems).
2. Light structure and high dynamic performances: max velocity is about 3,5 m/s and max acceleration is, in the present configuration, about 40 m/s^2 with a load at the end-effector of about 5 kg (to enhance the dynamic performances, innovative materials and linear motors can be used)
3. For the model with 6 d.o.f., the kinematic behaviour of the 4^{th} axis is completely independent from the other machine axes and could perform a 360 deg orientation.
4. Due to the particular U-joint positioning, the motion transmission for the 4^{th} and 5^{th} axis actuation (from motors to the machine movable platform) is constant-velocity.
5. Due to the particular U-joints positioning the movable platform movement produced by the three linear actuators is always a pure translation independently from the displacement of the 4^{th} and the 5^{th} axis.
6. Introducing an additional axis to the machine (the redundant translational axis) the triangle works "in plane" all over the workspace.

MAIN APPLICATIONS

The main applications of this machine, according to the different morphologies, can be:

- Packaging and load/unload of belt conveyors
- Fast pick & place of small and medium size objects
- Laser and WaterJet cutting
- Spraying and gluing

With a heavier mechanical structure sizing, other application are foreseen; application which combine the use of a robot with the use of a press. These applications include, but are not limited to: riveting, shearing, deeping-draw, caulking, stapling, keying.

MACHINE INVERSE KINEMATCS AND WORKSPACE

All the analyses described from this point to the end are related to the spatial four d.o.f. machine.

The first simulations done to check the machine behavior try to investigate the workspace and the machine stiffness. In particular, the machine inverse kinematics is analyzed and the Jacobian matrix is computed.

The meaning of each kinematic chain vector (Fig 4) is:

- q_i: position of the i_{th} slide on the sliding rail
- a_i: height of each slide (constant vector)
- $b_i = d_i$: length of skewed U – joints
- c_i = leg of the i_{th} strut
- v = height of the frontal triangle
- h = base of the frontal triangle
- ci_{pp} = projection of each strut on the plane
- e = length of the mobile platform

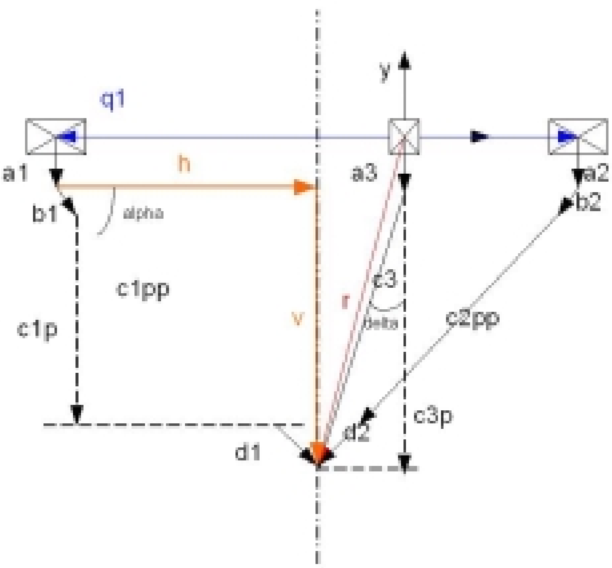

Fig. 4 – Machine Model used to investigate the workspace

The machine inverse kinematics equations are very simple. In particular for the frontal struts we get:

$$c_{ipp} = \sqrt{c_i - (z-e)^2}$$

The two angles orientating the frontal struts are:

$$\alpha = \arcsin\left(\frac{y + a_i}{d_i + b_i + c_{ipp}}\right)$$

$$\beta = \arcsin\left(\frac{z-e}{c_i}\right)$$

The height and base of the frontal triangle are:

$$v = y + a_i$$

$$h = \sqrt{\left(c_{ipp} + b_i + d_i\right)^2 - v^2}$$

The positions of left and right slides are:

$$q_1 = x - h$$

$$q_2 = 2h - q_1$$

For the rear strut (i = 3) we can use a similar approach:

$$c_{3pp} = \sqrt{c_3^2 - x^2}$$

$$v_r = y + a_3$$

$$h_r = \sqrt{c_{3pp}^2 - v_r^2}$$

The position of the rear slide is:

$$q_3 = z - 2e - h_r$$

The angles orientating the rear strut are:

$$\gamma = -\arcsin\left(\frac{v_r}{c_{3pp}}\right)$$

$$\delta = \arcsin\left(\frac{x}{c_3}\right)$$

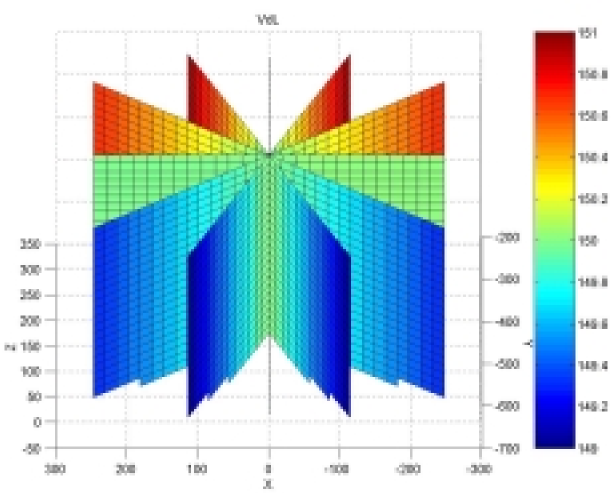

Fig 5 – Four d.o.f. Machine Workspace

The workspace is a parallelepiped of about 500 x 400 x 400 mm which a strut sizing of 400 mm for the two frontal struts and 500 mm for the rear strut, as shown in Fig. 5.

ADAMS MODELS AND SIMULATIONS

For the same machine configuration, some simulations were done using ADAMS®. The machine features are:

- Maximum acceleration: 40 m/s^2
- Maximum velocity: 3,5 m/s
- Max. Payload: 5 kg for an acceleration of 40 m/s^2
  20 kg for an acceleration of 10 m/s^2
- Maximum working force at end-effector: 100 N (in each direction)
- Maximum working torque at end-effector: 10 Nm

The simulation results indicate that the machine is able to reach the rated performances. In particular the machine reaches its standard working condition with a maximum motor force of about 600 N. A drawback of this architecture are the forces acting on the struts. Due to this configuration the two frontal struts are twisted by a torque which can reach 30 Nm, depending on the working conditions, as illustrated in Fig. 6.

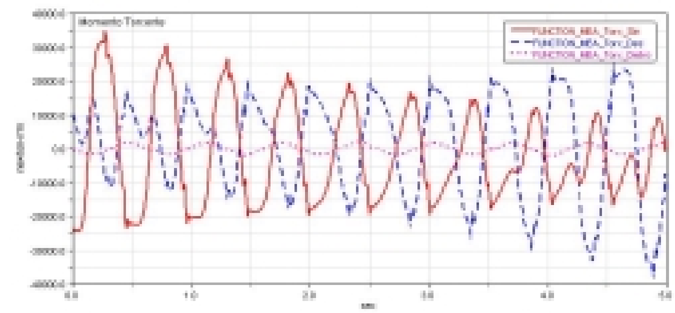

Fig. 6 – Torque of the two frontal struts in the 4 d.o.f.

It is then necessary to size the legs in such a way that the maximum torque doesn't affect the required stiffness at the machine end-effector.

A SOLUTION TO IMPROVE THE MACHINE STIFFNESS

The proposed solution to decrease the strut bending and torque moments is the coupling of two modular struts. In this way we get a parallelogram as illustrated in Fig. 7.

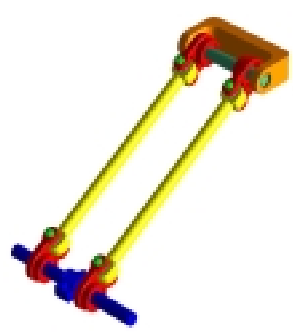

Fig. 7 – A parallelogram module composed by two struts on Fig 1

This item is another modular machine element.

Introducing two parallelograms in the frontal machine triangle we get an over constrained machine, which has the same kinematics behavior but an increased stiffness; this increase is due to struts stressed mainly in the axial directions, even if universal joints are installed on both the leg extremities.

Fig. 8 shows the same machine architecture illustrated in Fig. 3 after the parallelograms introduction.

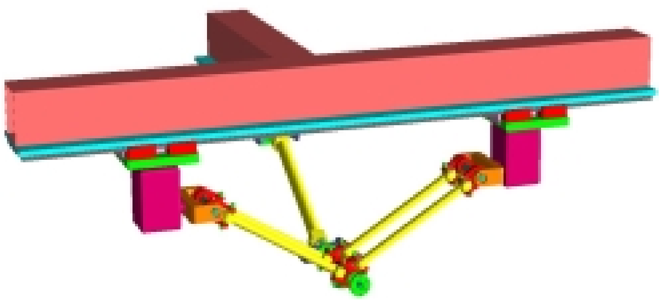

Fig. 8 – The same machine architecture showed in figure 3 after the parallelogram introduction

The same simulations done on the spatial architecture of figure 3 are repeated for this improved machine. The results are given in figure 9 and demonstrate that bending and torsion moments are limited to a maximum value of about 0.5 Nm.

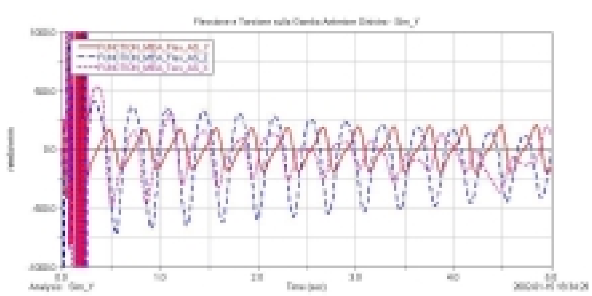

Fig 9 – Torque and bending moments in the frontal struts

FRAME ANALISYS

Some FEM analyses are done to test the machine frame stiffness using I-DEAS®. In particular the static displacement and the vibration mode are analyzed (Fig 10). The results give a maximum displacement of 0,114 mm under the dynamic forces executed by the machine during operation. For the vibration modes the frame has the first vibration mode at 43 Hz (flexion around X axis), the second at 50,4 Hz (flexion around Z axis) and the third at 63,4 Hz (torsional, around Y axis)

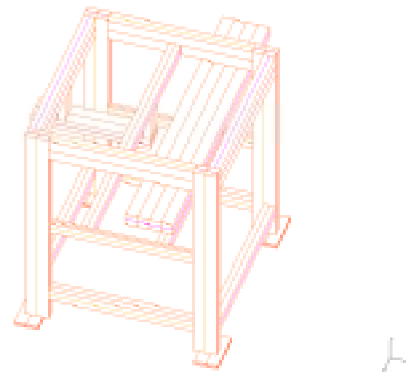

Fig 10 – FEM model of machine frame

CONCLUSIONS

This paper shows a new approach which joins the advantages of PKM and RMT. In particular some modular machine elements are introduced (Fig 1 and 7). Using these elements it's possible to build completely modular and upgradeable machines which embed the possibility to adapt their d.o.f. and their stiffness to the particular task. Gathering more RMT on a production plant it will be possible to exchange modular machine items from a machine to another according to the production needs.

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