6 DOF, Low Inertia, Concept Design for an Industrial Robotic Arm

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***Abstract*—Serial robotic arms are a central part of most manufacturing industries and are widespread. They are used for component assembly, welding, cutting and spray painting, but can be programmed to accomplish a wide variety of tasks within its workspace. Due to the location of the motors and gearboxes the serial arm contains significant inertia, which is a significant disadvantage. It affects accuracy and contributes to dynamic vibration problems. The research presented here will focus on a novel hybrid machine design to overcome these problems. Its architecture is hybrid as it does not explicitly conform to the exact definition of either Serial Kinematics Machines (SKMs) or Parallel Kinematics Machines (PKMs). The goal of its hybrid nature is to combine the best advantages of both architectures which is to have an optimized workspace to footprint ratio equivalent to that of a serial robot, with the machine moving mass and agility of a parallel robot. These advantages are conflicting requirements and do not coexist in pure serial or pure parallel topologies. The unique hybrid design presented here, uses a few novel mechanisms that enables a full range of 6 DOF (degrees of freedom), with the advantages mentioned and thus has the potential to be a better option to present-day industry technology.**

Keywords-Serial kinematics, parallel kinematics, hybrid machine, 6 DOF

I. INTRODUCTION

A serial robotic architecture is an open kinematics chain in which each actuator axis follows in linear succession (where each motor and gearbox is positioned at or close to the specific joint it controls). In a pure parallel architecture, all the actuators have a fixed arrangement and position in space, and a number of arms and links are coupled in parallel from the actuators to the end effector and form closed kinematics chains. Examples of PKMs are the 3 DOF Delta and the 6 DOF Hexapod. Both architectures are complementary with regard to their advantages and disadvantages; PKMs are faster, stiffer and more accurate whereas SKMs have a large useful work volume, are more adroit and multipurpose.

Industrial robots that combine the benefits of both types of architectures can improve manufacturing processes. The objective of this paper is the conceptual design of such a machine. The progression of automation and flexible production demands new applications with improved performance from industrial robots. Hybrid structures surpass the performance limitations of pure serial and pure parallel robot technology, and are the route to improved industrial robotics.

II. COMPARING PARALLEL AND SERIAL ARCHITECTURES

Parallel architectures have the benefits of enhanced stability and pose rigidity. They are also more repeatable due to reduced arm flexing and they can apply large forces in its work volume. [1]

The velocity profile of the end effector is greater, as the motors that carry most of the manipulator’s mass are kept stationary at the fixed base, in contrast to a serial architecture, which moves most of it. [2]

The mass of the end effector and payload is divided among many supporting links in the closed kinematic structure. [3]

The inertia of SKMs is significant when compared to PKMs since each structural component in the kinematics chain has to support its mass and that of its motor, coupled with the masses of all the structural and drive units preceding it. This mass distribution places severe limitations on the ability of the robot with regard to its dynamic performance and acceleration. [4]

Furthermore, flexing errors in the serial chain are cumulative, resulting in a greater total end-of-arm flexing error as compared to PKMs. Manufacturing errors, gear backlash, hysteresis, etc. in a serial structure are additive resulting in a larger global error. On the other hand PKM structures have the inherent nature of averaging all errors. By using large displacement compliant-joints accuracy can be in the order of microns. [5]

PKMs offer varying designs allowing robotics engineers creative freedom unlike the design limitations of serial architectures. They are relatively insensitive to temperature fluctuation, use less power, come at a reduced manufacturing cost and are more dependable. Their most significant disadvantage is that their footprint or volume of space that is enclosed by the kinematic structure is large in comparison to the volume of space in which the end effector can move. Some exceptions do exist but most take up a sizable volume. Optimal design is also required as their geometry greatly influences their performance. [6]

End effector payload fluctuations also significantly affect machine behaviour, as the ratio between payload and machine moving mass is considerably higher than in SKMs. Control is also more challenging as PKMs have complex kinematic and dynamic models. [1]

PKMs with 6 DOFs have small useful work volume, are plagued by design complications and their forward kinematics is an exceptionally hard problem. PKMs with 2 and 3 DOFs can easily be described as closed forms. All the singular points of a 6 DOF parallel mechanism cannot be found easily, but can be for PKMs with 2 and 3 DOFs. Hence, lower DOF PKMs have been attracting more attention for industrial applications. [7]

III. DESIGN NOVELTY

The hybrid design consists of a unique concentric gearing mechanism, multiple 3 bar linkages and a 3 DOF wrist. It has 6 DOF, has the same motion capability and occupies a similar volume to that of a typical serial robot. All 6 motors and their associated gearboxes are fixed to the base and through the 3 bar linkages they transfer their torque to control their specific axis. Since the motors are no longer on the arm, its inertia is reduced, and a further mass reduction can be made using lightweight materials and composites for the structural linkages. This solution still has to be researched thoroughly but it represents the first step towards a functioning practical solution.

Typically, when robotics engineers create hybrid machines they connect serial and parallel structures serially. The constituent parallel and serial sections of the structure can be recognized easily. The aim of these hybrid machines is to concentrate a particular architecture at the place where its benefits are most useful, and it draws on the advantages of both topologies in a global sense. Low DOF (4 or less) PKMs are used as construction blocks. SKM components are used where a large degree of motion is essential or where there is no simple PKM solution. The concept machine to be described has no distinct parallel or serial building blocks and no clear conclusion can be drawn as to a parallel or serial nature. It is a truly unique hybrid structure.

IV. HYBRID DESIGN DESCRIPTION

The design centers around the concept of fixing the motors and gearboxes in one location (which makes this design similar to a PKM) and transferring actuation to a specific axis located elsewhere, via a set of gears and light-weight connected linkages. This actuation transfer can be realized in 2 ways through a set of rigid links or non-rigid torque transfer mechanism. The non-rigid torque transfer option would use toothed belts or chains, but would reduce the payload carrying capability and machine's output force. On the other hand, it does offer an increased manipulator velocity profile and this would suit applications that require the spatial manipulation of light objects in a large workspace. For now our focus in this paper is on designing a rigid link machine but the belt or chain drive option remains a design challenge for a future date. The illustrations depicted here are from a rapid prototype Perspex platform. All mechanical components i.e. links, gears and structural elements were laser cut from 2D sheets of Perspex, and 2D components were then assembled into 3D structures. The design requires bevelled gearing and to work around that obstacle the spur gear teeth were made large enough so that where needed they could mesh at 90º and in this case their

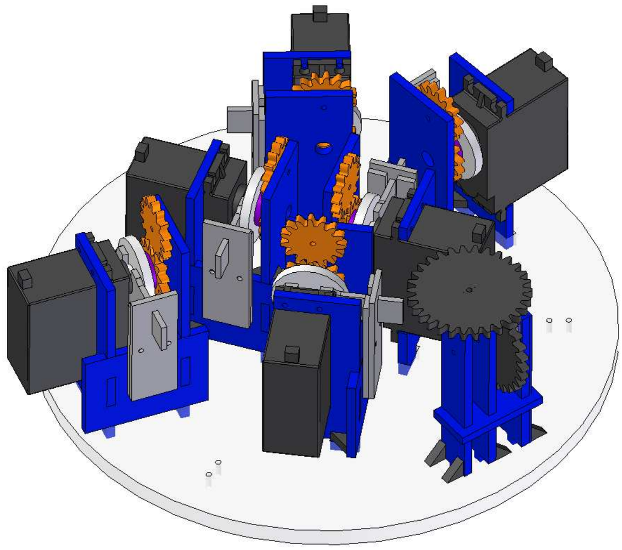

Fig. 1. Motors and gearboxes fixed to machine base

pitch circles would be tangent at 90º. This substitution functioned adequately, in spite of the fact that the gears now make contact at a point instead of line. For a working model the use of such gearing was sufficient. Most of the illustrations that follow will show this type of gear meshing but it must be born in mind that they represent bevelled gears, and those will work far better.

The design will be described from the bottom up. The motor units and their associated gearboxes (shown in Figure 1) have a fixed position in space (6 sets in all). Their arrangement allows them to occupy dedicated space for themselves, and to mesh with the gears of the next part of the design, the concentric gear drive. Those gears that mesh with the concentric drive have to be bevelled as they mesh at an angle, preferably at 90º.

The concentric gear drive consists of 7 concentric sections. The outermost section is part of the fixed base and does not move relative to the 6 inner sections. The 6 inner sections are all capable of rotating independently of each other (just one degree of freedom, i.e. rotation), while remaining concentric.

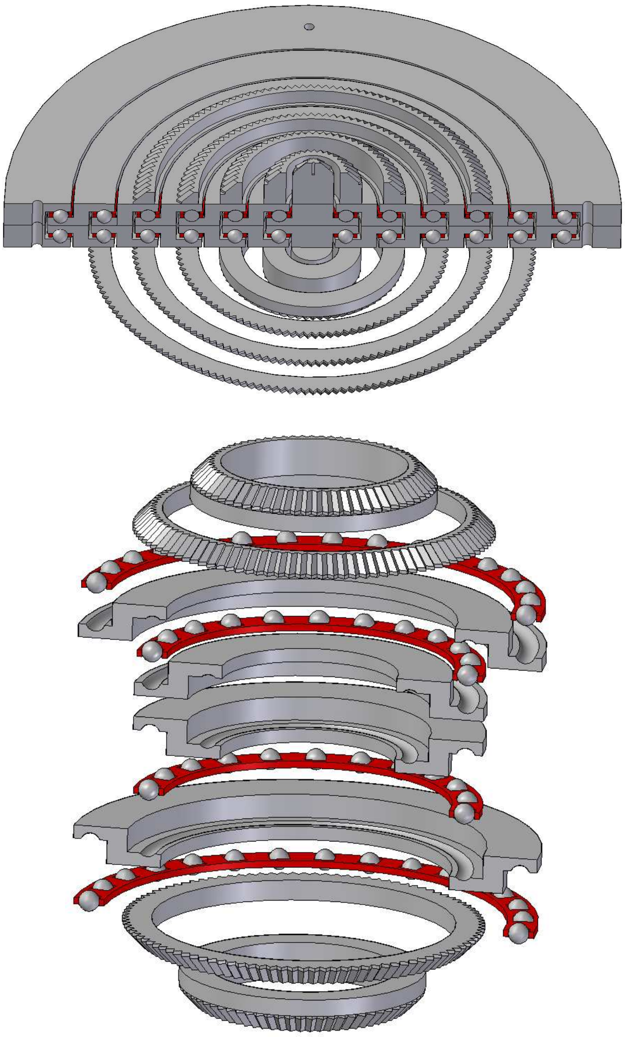

Fig. 2. Concentric gearing mechanism illustrating double ball race bearing, and bevelled gears on both the top and bottom halves

Each section holds its nearest inner section in place (the innermost section does not hold anything), via a double ball race bearing (illustrated in Figure 2). The inner bearings do not carry a vertical load, they simply facilitate the transfer of rotation and torque from the base motors to the designated driver gears/links. The outermost bearing is the only one that carries a vertical load, which is the complete mass of the moving machine and the payload it carries.

The 5 innermost sections have bevelled gears mounted on both the top and bottom halves of each section (Figure 2). The 6th section (counted from the inside moving outward) has a bevelled gear only on its bottom half. On its top half it has a physical mounting for 5 bevelled gears that have all their axes concentric and which mesh with the top half gears of the concentric gear drive at 90º (Figure 3). The 6th section (outermost movable section, see Figure 2) is responsible for moving the mobile parts of the machine arm about the vertical axis.

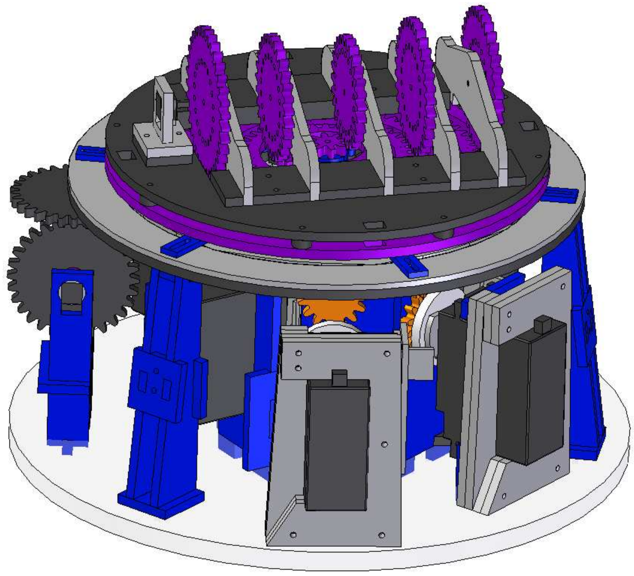

Fig. 3. Bevelled gear mounting on top half of concentric gear drive

To transfer actuation away from the base, 3 bar slider-pivot linkages were used, which is illustrated in Figure 4. The orbit of the follower need not be a 1 to 1 ratio (the output link would trace a circle of the same radius as the driving link) or 1 to -1 (the output link would trace a circle of the same radius as the input link but in the opposite direction) match with the driving link. The follower links must however match the angular rotation of its driver (no longer positional magnitude); that is the orbit does not have to be a perfect circle but it has to circumnavigate the axis, i.e. the follower must have one complete orbit for every 360º rotation of its driver. This orbit of the linkage output point also implies that the torque (and rotational speed) delivered to the next link in the chain will vary.

The slider has a pivot at the midpoint of the supporting link, allowing it to rotate. This position minimises warping of the follower orbit and maintains a somewhat circular profile. Furthermore, the follower on the end of the primary slider-bar linkage becomes the driver to secondary stage. The orbit of the follower on the secondary stage is further warped but still circumnavigates the main wrist axis, and matches each degree of rotation of the driver on the primary stage. Our initial choice for this torque transfer linkage was a parallelogram but there was no simple mechanical solution to prevent the singularity position (when the parallelogram collapses, or adjacent sides become collinear, and the exit configuration in which it could either be the parallelogram or a crossed quadrilateral – crossed configuration parallelogram). We experimented with designs in which we used extra links to create double parallelograms, with a phase offset so that when one collapses the other prevents the crossed configuration. Another solution was to maintain a crossed configuration, which used a moving slider-pivot joint between the longer sides of the quadrilateral (parallelogram in crossed configuration). The 3 link slider-pivot linkage in Figure 4 above was the simplest solution to achieve the required objective.

Three of the inner vertical bevelled gears, being driven by the concentric gear drive, then serve as the driver links for the primary slider-bar linkages. These 3 gears then drive the secondary slider-bar linkages that eventually control the orientation of the wrist through the wrist concentric drive (Figure 4). The 4th vertical bevelled gear controls the proximal arm (lower arm, as it is closer to the fixed base) whose midpoint holds the pivot axis that connects to the sliders on each of the 3 primary slider-pivot linkages. It controls the elevation of the lower arm (proximal arm) with regard to the

Fig. 4. Primary and secondary 3 bar slider-pivot linkages

horizontal plane. The 5th gear controls the driver of a 3 bar slider-pivot linkage whose follower controls the angle between the upper arm (distal arm) and the lower arm (proximal arm).

The distal arm holds the axis that connects to the sliders of the 3 secondary slider-bar linkages (Figure 8). The slider-pivot of the upper arm is located at the mid-point between the end rotational joints. This reduces the warping of the secondary stage follower orbit, much like with the primary slider-bar linkages.

The follower end points on the three inner slider-pivot linkages of the secondary stage then connect to 3 vertical bevelled gears respectively (which are mounted on the upper arm). Since the follower does not have a perfect circle orbit around the main wrist axis slots are cut into the gears and links allowing the follower to move in and out of a perfect circle trajectory/orbit. These slots are slider-pivot joints.

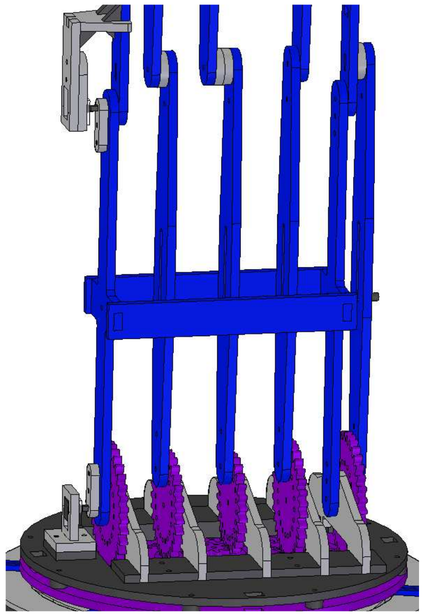

Fig. 5. Vertical bevelled gear connections to primary 3 bar slider-pivot linkages

Those vertical concentric bevelled gears then mesh with the

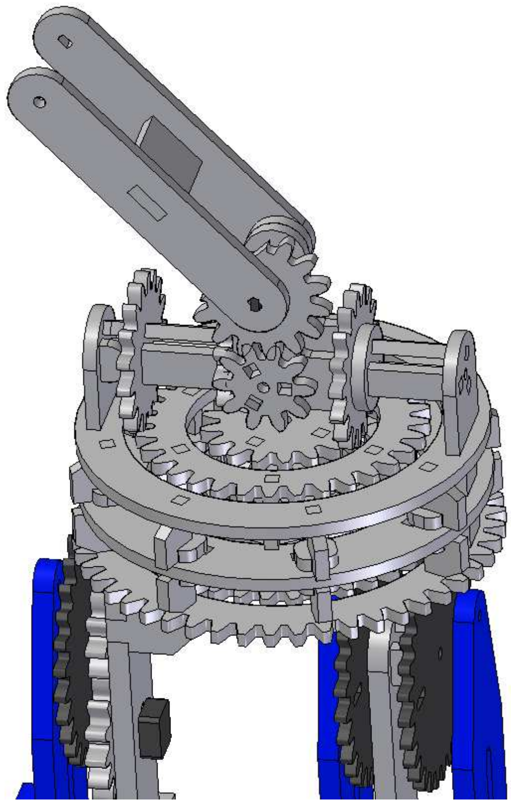

Fig. 6. 3 DOF wrist which uses the same type of concentric gearing mechanism used at the base

wrist concentric drive gearbox having 4 concentric sections shown in Figure 7. This concentric drive again makes use of the double ball race bearing illustrated in Figure 2, which allows each section to move independently of each other. The outer sections hold the inner sections in place. The outermost movable section (or the third section in the concentric gear drive for the wrist) rotates the wrist (this is the first axis) and has mountings for the inner 2 axes, of the 3 DOF wrist (Figure 6, 7). With some additional gearing those remaining 2 axes are set at 90º to each other and the 1st wrist axis, thus allowing a full 3 DOF orientation of the end effector.

V. CONCLUSION

A cheap Perspex model was built (Figure 8) around the hybrid machine design to prove the concept. At present the model has 4 working DOFs, 3 which position the wrist and 1 to orient it. The last 2 DOFs could not be completed as the improvised Perspex bearings for the concentric gearing mechanism became problematic. 3D printing technology will

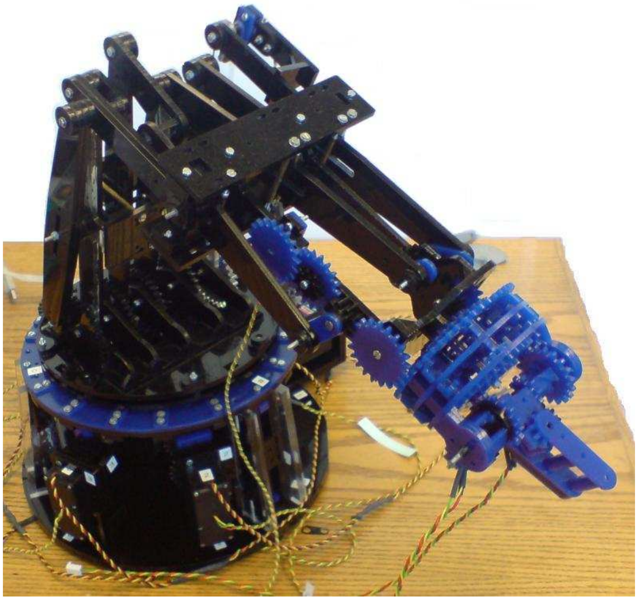

Fig. 8. Complete motorized Perspex model

be used to rapid-prototype proper bevelled gears for the next design iteration. The final goal is to construct a full scale prototype of the design. As well as test and compare the results with an existing serial robot, to validate the performance claims made earlier. We are at present in the process of sourcing adequate funding to continue with the research and development. Future research papers will tackle issues of force transfer from the base through to the correct axis, vibration in the mechanism, machine kinematics and dynamics, and other important measurable or simulated data that will be used to make an effective comparison of our design to current industry standards.

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