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Spherical Wrist for CNC Sheet Metal Cutting Machines Application

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Abstract. *This work presents the development of a spherical wrist, to be applied in CNC plasma cutting machines. Spherical wrists are robotic devices that decouple the position and orientation in robot manipulators, and are used when operations need dexterity from the manipulator. In CNC cutting machines, they make possible bevel cutting in sheets and tubes and reaching new cutting positions. Initially, research is made on scientific publications and manufacturers of similar devices, from the most used mechatronics solutions and applications of these devices on sheet metal cutting. Next it is presented a virtual prototype of the solution to be implemented, and the direct and inverse kinematics based on this solution are presented, with results that confirm accuracy of the developed kinematic model.*

Keywords: *Wrist; Spherical Wrist; Robotic Wrist; Bevel Head; Plasma cutting bevel head.*

1. INTRODUCTION

The usage of plasma as a cutting tool was patented by Gage (1957) as a variation of the TIG welding process. Since then developers created several cutting methods using plasma as the main element. The plasma knowledge has been through a long development process, today's expectation is that plasma cutting gets as precise as laser cutting.

As plasma equipment is low cost, it is expected to be the main competitor in today's laser cutting market. After oxygen and air became popular plasma generating gases, the major problem to be faced is the low consumables life cycle. It is expected that in the future the consumables life cycle to be considerably extended, reducing the process cost and increasing the applications of plasma cutting.

Cutting robots have been utilized in a ever increasing gamma of heavy operations, mainly in steel. Some example include pressure vessels parts manufacturing, cut and preparation of piping for the oil and gas, naval and subsea industry.

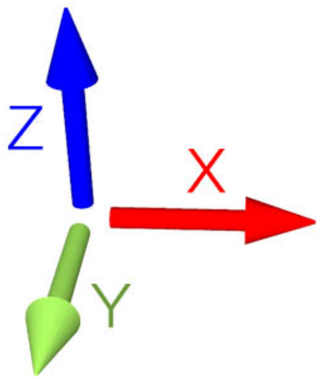
Bogue (2008) presented a case about the manufacturing of pipes for nuclear ships in Newport News Shipbuilding, inc. In the process, several stages of manual oxy acetylene cut were involved, what made it slow and gave it a high part rejection rate, even in the simplest joints. The process then was replaced for five axis plasma cutting robots, substantially reducing the cutting and welding preparation time, besides improving the overall quality. An economy of $ 30 million USD per robot per year was the result.

The development of new wrist devices follows two main lines: spherical engines and mechanisms. Spherical engines are electrical engines with two or more rotating degrees of freedom, they usually present small torque and workspace but work at high speed, specially useful in laser cutting. Lee *et al.* (1994) developed a design of an engine operated on the principle of variable reluctance, which allows high positioning resolution and of simplified manufacturing. Mechanism based spherical wrists present relatively large workspace and torque. The best known examples of these are the parallel manipulators, known as Stewart Platforms. A Stewart platform is a manipulator that works with six prismatic actuators. The most notorious use of these platforms is on the LIDS (Low Impact Docking System) technology from NASA, where the manipulator is used in the coupling of the Space Shuttle in the International Space Station. Another studied mechanism based spherical wrist was developed by Puglisi *et al.* (2012) for a needle insertion guidance robot. This wrist is coupled to a serial arm, thus needing to be compact and lightweight.

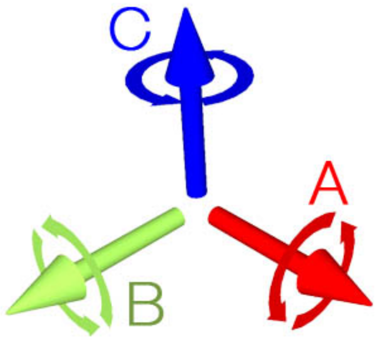
Another of the most used mechanisms is the spherical parallel manipulator. It joins the advantages of the parallel manipulator high mechanical stiffness and movement precision, desirable characteristics in a high performance spherical wrist device. One example of spherical parallel manipulator studied was developed by Bai and Hansen (2007), their design is curious for it allows unlimited rolling.

The plasma cutting robots market follows a path that will lead it to have the same quality as laser cutting, reaching new potential clients that need good precision in a fraction of today's price. The development of new parallel spherical wrists free of gear composition must follow the high precision plasma torches released in the last decade. Hypertherm, Inc. (2001).

The CNC plasma cutting market has expanded to more sophisticated applications. Therefore, a bevel head is an important add-on and with increasing demand. The manual beveling method consists on beveling the part after the cut,



(a) XYZ System



(b) ABC System.

Figure 1. Coordinate axis.

(a) Messer skew rotator.

(b) Esab VBA Global.

Figure 2. Some design examples from Messer Cutting Systems (2014); ESAB (2013)

using manual tools. This operation can take up to a few man hours and risks deforming the unfinished part, also delaying serial production.

In this paper is presented a spherical wrist device, designed to be used as a bevel head in a plasma cutting machine. It is presented a virtual prototype of the solution to be implemented, and the direct and inverse kinematics based on this solution are presented, with results that confirm accuracy of the developed kinematic model.

2. INITIAL DEVELOPMENT

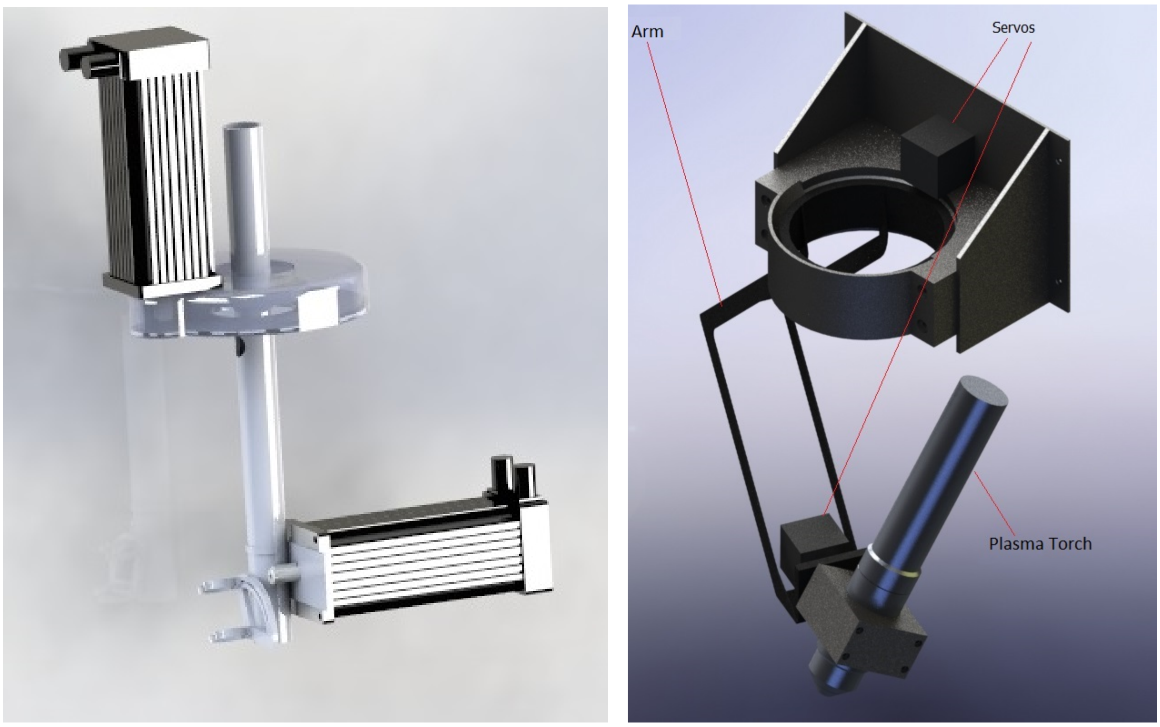
2.1 Industrial spherical wrists applied to plasma cutting operation

The first step in the development of a product for CNC cutting machines is to understand the CNC system. It uses Cartesian coordinates to numerically give direction and movement plan to a train of engines. A Cartesian coordinate system is made of reference lines called coordinate axis. These coordinate axis are measured in a same unit of length, that in the CNC system is usually millimeters of inches.

The coordinate system allows the CNC machines to be controlled in each plane of movement. In Figure 1(a) is shown the basic and in Figure 1(b) the advanced coordinate axis of a CNC machine. The XYZ system grants the machine the ability to cut bi-dimensional profiles at given heights. This movement is adequate for most CNC applications, like milling, turning, laser, plasma and 3D printing.

When the user requires more advanced functions that the ones presented by the XYZ system it must uses the ABC axis, where A is the rotation along the X axis, B is along Y and C along Z. These new axis give the user the power to not only move about the 3D machine, but also the power to rotate along any axis. With this the CNC system can work anywhere in the 3D space, the only limits to the operation are facts like the size and the machine design.

Among the existing models in today's market, the widely known models are the Skew Rotator from Messer Cutting Systems (2014) and the VBA Global Pro, from ESAB (2013), shown in the Figure 2(a) and *ESAB VBA Global*shown in the Figure 2(b). The models present many unique characteristics and an analysis of these shows the vantages and disadvantages of each, and points mainly to two properties: ESAB's wrist grants the centralization of the torch during all the rotating movement, making it easier to use the control software and granting the end effector position during all the cutting operation. Messer's wrist also has this property, but in a far more mechanically complex way.



(a) First design (b) Second design

Figure 3. Rendering of the Sextant and of the second conceptual design

2.2 The pre-development of the product

The main idea of the bevel head is to be a modular product, that can be sold as an add-on for the new and old machines, and so it's design must give as little intrusion as possible in the already existing machines. This brings several advantages to a company, that can include in the portfolio two separate machines and offer the new and old client separate versions of each. A client that uses the cutting machine without the beveling capability now can buy the add-on and increase his production. Still in the modularity topic, it's of utmost importance that the bevel head be adaptable to several of the torches available in the market.

3. DIGITAL PROTOTYPING

3.1 First conceptual designs

This design was the first created after the requisites studied, it was made to help in the comprehension of the system particularities. Shown in the Figure 3(a), it has been codenamed Sextant, for the similarity with the old navigating device. The main idea so far was to check the construction possibility with real sized engines and torches. The design workings predicted the torch cables to be inside the center pipe, latelly it was found to be impossible as there has to be a minimal opening for the torch cable radius. Hypertherm, Inc. (2009).

The second model shows great project maturity, with a design close to the final. The model also approaching assembly and adequate motorizing.

The model was changed for presenting fragility in the link between the torch and the top part, besides, the engines design were only conceptual, but already positioned in a region close to the final one.

The model in this stage incorporated the correct cable idea on the interior of the main opening and the centralization of the torch. It is shown in Figure 3(b).

3.2 Construction Design

In this model the servomotors are standard with low backlash gearboxes. In each gearbox the backlash specified by the manufacturer was less than two minutes. One of the gearboxes is a ninety-degree turn, to reduce the dead space in the machine while in use. Also a change is presented in the torch and in the assembly device, adequate to an ample gamma of commercial plasma torches. In this version it was also inserted a bodywork that protects the gears from the hostile environment of the factory, without that, metallic dust from the cutting might intervene with the adequate works of the gears.

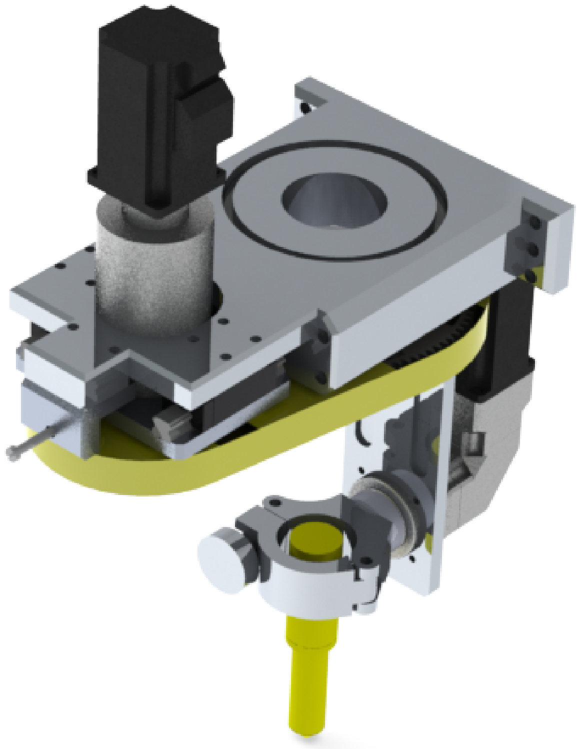


Figure 4. Rendering of the Final Design.

The wrist was already production-ready, with some differences from its conceptual design. The greatest changes were the arm and the bearings, while the latter used one angular contact bearing and one axial needle roller bearing, the final version uses two angular contact bearings. This change was made after it was verified that the needle one could go out of alignment, bringing undesired vibration to the system. The design is shown on Figure 4.

Also were made weight reduction in the straight section of the arm and in the gears, as it was not subject to excessive loads that might bring in material failure. The weight reduction is important to keep the interchangeability among parts, as it could make the wrist feasible even in old cutting machines, with inferior motorizing.

An exploded view of the wrist is also shown in Figure 5, in which it shows the remarkable parts of the assembly. In this Figure we can see the internal workings of the machine and its composition: 1 stands for the servomotors, which were chosen for the great positioning precision. The low backlash gearboxes are marked as 2, one of these presents a ninety-degree angle which was chosen to minimize operating space. 3 is a backlash reducing system, which pushes one gear against the other. This system is needed to avoid precision loss during the movement of the C axis.

In Figure 5, number 4 stands for the plasma torch, the design comes from Hypertherm, Inc. (2009). Number 5 are the angular contact bearings, which were chosen for low price, ease to find in the market and ease of alignment, that was a problem in the needle roller bearings. 6 stands for the machine base assembly, as the spherical wrist is a modular product it uses simple bolts to attach to the machine. Finally, 7 stands for the opening where the torch and engine cables go trough, this was a design choice to avoid entangling of the cables during the machine operation.

4. MODELLING

4.1 Direct Kinematics

The direct kinematics of the spherical wrist was developed using a symbolic math program. To simplify calculations an 2D model of the wrist, shown in Figure 6, was created. In Equation 1 it is shown the Z coordinate of the position vector related to the origin, which is in the link between the bevel head and the CNC machine.

$$z_3^0 = 1/2\, d_5 \sin(\alpha_1 + \alpha_2 + \alpha_3 + \theta_2) + 1/2\, d_5 \sin(\alpha_1 + \alpha_2 + \alpha_3 - \theta_2) - \cos(\alpha_1 + \alpha_2 + \alpha_3)\, d_4 + \cos(\alpha_1 + \alpha_2)\, d_3 - \cos(\alpha_1)\, d_2 - d_1 \quad (1)$$

Using the symbolic math software together with the 3D CAD, the transformation matrix was tested. The values of

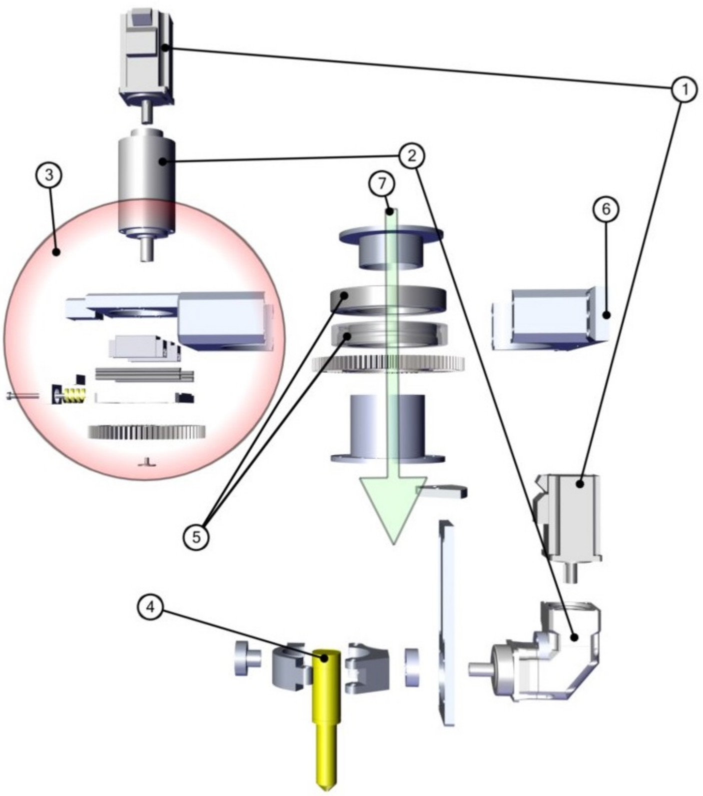


Figure 5. Exploded view of the Final Design.

length and angle used were extracted from the 3D model. In Table 1 are shown the values for the joint angles.

Table 1. Values for the final geometry of the wrist

Nome	Valor
θ_1	0 rad
θ_2	$\pi/3$ rad
θ_3	0 rad
α_1	$\pi/2$ rad
α_2	$\pi/2$ rad
α_3	$\pi/2$ rad
r	100 mm
d_1	96 mm
d_2	71,2 mm
d_3	185 mm
d_4	71,81 mm
d_5	148,97 mm

In Table 2 are shown the values for the position with the torch rotated in a 60^o angle in the CAD model compared to the calculated values. It is notable that the small rounding error got up to 1% with the complex calculations. The method used in the direct kinematics calculations is the same used in Jazar (2010).

4.2 Inverse Kinematics

The inverse kinematics was calculated using the method from Paul (1981), with a symbolic math software. The equations from 3 to 5 relate to the degrees of freedom of the wrist, implying that the matrix ${}^3T_6$ from equation 2 is the resulting matrix from the transformation between the base of the CNC machine and the extremity of the torch.

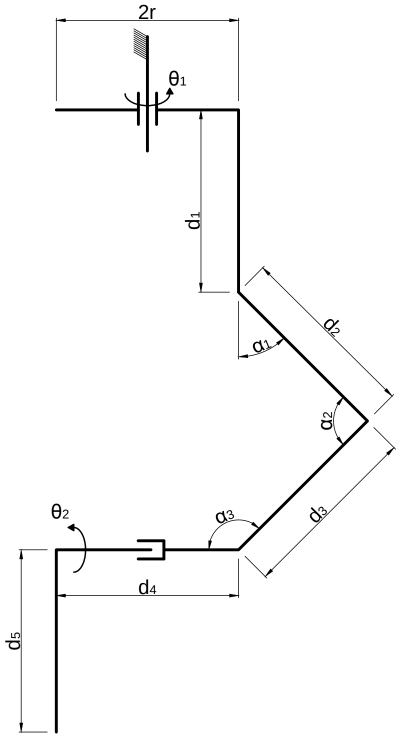


Figure 6. Simplified model in the yz plan, showing the degrees of freedom and geometry of the device.

Table 2. Direct Kinematics data validation for theoretical values

Coordinate	Calculated	Verified	Error(%)
x_3^0	93,517	93,530	-0,013
y_3^0	49,000	49,000	0,0
z_3^0	-295,4475	-295,000	0,151

$$ {}^3T_6 = \begin{bmatrix} n_{13\,x} & s_{13\,x} & a_{13\,x} & p_{13\,x} \\ n_{13\,y} & s_{13\,y} & a_{13\,y} & p_{13\,y} \\ n_{13\,z} & s_{13\,z} & a_{13\,z} & p_{13\,z} \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{2} $$

$$ \theta_1 = \arctan\left(\frac{-p_{13\,x} + d_5 n_{13\,x}}{-p_{13\,y} + d_5 n_{13\,y}}\right) \tag{3} $$

$$ \theta_2 = \arctan\left(\sqrt{\frac{-1 + 2\,{n_{13\,z}}^2 + \cos\left(2\,\alpha_1 + 2\,\alpha_2 + 2\,\alpha_3\right)}{-1 + \cos\left(2\,\alpha_1 + 2\,\alpha_2 + 2\,\alpha_3\right)}}\sin\left(\alpha_1 + \alpha_2 + \alpha_3\right) * \left(n_{13\,z}\right)^{-1}\right) \tag{4} $$

Equation 5 refers to an unexisting axis in the design using plasma cutting but can be useful in other situations, like a claw or another kind of mechanism that uses the third degree of orientation. In plasma cutting, the torch rotating along its own axis is irrelevant.

$$ \theta_3 = \arctan\left(\frac{-a_{13\,x}p_{13\,y} + a_{13\,x}d_5n_{13\,y} + a_{13\,y}p_{13\,x} - a_{13\,y}n_{13\,x}d_5}{-s_{13\,x}d_5n_{13\,y} - s_{13\,y}p_{13\,x} + s_{13\,x}p_{13\,y} + s_{13\,y}n_{13\,x}d_5}\right) \tag{5} $$

For the validation of the inverse kinematics, the direct kinematics matrix was extracted from the 3D design, shown on Equation 6 for the sixty degree angle on θ_2, from Figure 6. Replacing the data, the data on Equation 4, the right value of the angle can be found,as shown in Equation 7.

$$
{}^{3}T_6 = \begin{bmatrix} 0,866 & 0,500 & 0,000 & 129,012 \\ 0,000 & 0,000 & -1,000 & 99,390 \\ -0,500 & 0,866 & 0,000 & -355,485 \\ 0,000 & 0,000 & 0,000 & 1,000 \end{bmatrix} \tag{6}
$$

$$
\theta_2 = \arctan\left(\frac{\sqrt{\frac{-1+2(-0,5)^2+\cos(2\pi/2+2\pi/2+2\pi/2)}{-1+\cos(2\pi/2+2\pi/2+2\pi/2)}}\sin\left(\pi/2+\pi/2+\pi/2\right)}{-0,5}\right) = 60^o \tag{7}
$$

5. FINAL REMARKS AND FUTURE WORK

It was developed a robotic spherical wrist of simple construction and application in plasma cutting machines. The wrist presents two degrees of freedom and an inactive third one, that could be used if need be.

The wrist had its direct kinematics developed using homogeneous equations and the inverse kinematics based on Paul (1981). The kinematic model was validated using 3D CAD and symbolic math software, which are enough to corroborate the equations and implement them in a machine controlling software.

As for future work, there is a prototype under construction, which is intended to test the main requirements of adaptability and modularity. In a future article the experimental results will be presented, along with the G-Code generation software for 2D DXF drawings.

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