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Design, analysis and testing of a 5-axis solution for water jet cutting

K. Andersson, A. Kutlu, M. Langenoja, J. Rosengren, M. Sosa
KTH, School of Industrial Engineering and Management, Dept. of Machine Design
Email: kan@kth.se, kutlu@kth.se, langen@kth.se, jroseng@kth.se, msosa@kth.se

Abstract
Abrasive water jet cutting is a technique which utilizes water mixed with abrasives, projected at high velocities to cut a wide range of materials. With a 5-axis solution for angled cutting chamfered cuts of material e.g. for parts that later are going to be welded and thus reducing one manufacturing step can be performed. This paper reports project work made in the MF2004 Machine Design advanced course at KTH. It describes the design and analysis of a first prototype (alpha prototype) of a 5-axis solution as well as the design of a second prototype (beta prototype). The selected concept is a tool center point (TCP) solution where the chamfer angle is realised by two rotations and the TCP position is independent of these rotations.

Keywords: 5-axis, water cutting, prototype

1. Introduction

Water jet cutting is a technique involving an ultra-high pressure water jet stream mixed with abrasive sand which wears off the material and hence cuts it [1].
One of the main advantages with water jet cutting is the ability to cut almost any material, the only criteria is that the material intended to be cut has to have lower hardness then the abrasive sand. Another advantage compared to other techniques like plasma, laser or gas (Acetylene-Oxygen) cutting, water jet cutting is a cold process meaning it leaves no Heat Affected Zone, HAZ, in the material. HAZ increases the brittleness of the material and hence decreases its performance.

2. Problem description

A 5-axis water cutting machine can perform movements in five different directions. Currently Kimblad Technology AB, Kimtech [2] uses the IHEAD solution for their 5-axis machine, see figure 1. This solution involves double angle actuation to perform a chamfer operation. The first angle (closest to the cut) is actuated using a four bar linkage mechanism. The mechanism is connected to a shaft which in turn is mounted on a motor. When the linkage mechanism rotates, one angle is changed and when the motor, holding the shaft, is rotated the other angle is altered. This results in a cone-shaped kinematic model.

2.1 The TCP idea

The TCP is a fixed point in space through which the water jet always will pass, independent of the angles described above. In this way, the kinematics of this concept principle will form the shape of a cone with its rotation axis through the point where the tool center point (TCP) is found. The advantage with this idea is the elimination of extensive movements in the X and Y axis of the machine.

Figure 1. The current IHEAD 5-axis solution used at Kimtech[1]

2.2 Requirements

The requirements below in table 1 are mostly based on the functionality of current 3-axis water jet machine at Kimtech with the additional functionality they want to introduce with this new 5-axis solution.

Table 1. Requirements for a 5-axis cutting head

Qualitative Requirements	Quantitative Requirements
The product must: • have TCP-kinematics • allow linear motion in XYZ-axis and rotation in A and B • accept a specific cutting head of type specified by Kimtech • transport high pressure water from mounting point to cutting head • transport sand from mounting point to cutting head • allow pneumatic on/off clutch for high pressure water in cutting head • measure Z-distance between head and material • avoid sensor failure due to collision with obstructions on the cutting table • cope with harsh environment of abrasive sand and water	*The product must:* • allow displacement no less than ±250° in B-rotation • allow displacement no less than 46° in A-rotation • complete 1 revolution in B-rotation in less than 1 second • change A-displacement from 0° to 46° in less than 1 second • allow linear max speed of no less than 1500 mm/min • allow linear max acceleration of no less than 2.5 m/s^2 • have Z-axis accuracy of Ø 0,1 mm or higher
The product should: • cut at continuous speed while changing direction and chamfer angle • consist of non-corrosive materials • look sturdy and robust • make neat circles	*The product should:* • weigh less than 15 kg • cut up to 200 mm thickness

2.3 Concept generation

An extensive background and benchmarking study was conducted before generating 5-axis head concepts for this project. The 5-axis solutions already on the market were searched and analyzed, not only for waterjet cutting machines but also for milling and plasma-laser cutting machines, see e.g. [3-8]. Among these, the solution from CENC Cut [6] has the desired TCP-kinematics. Thereafter, a number of concept solution were generated which, based on preliminary evaluations all have the potential to fullfill the listed requirements in table 1. Pros and cons were used to assess these concepts against the requirements, see table 2.

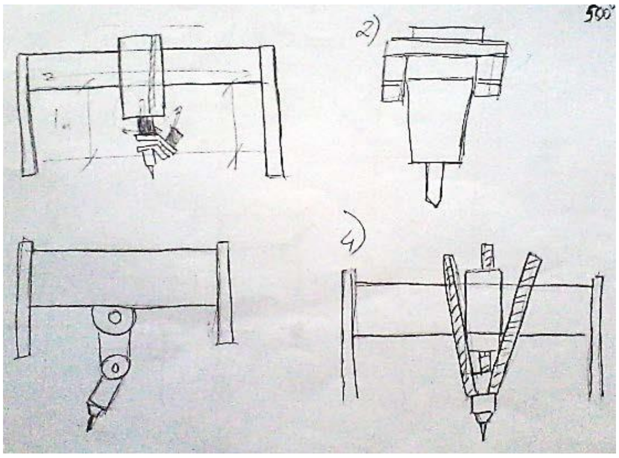

Figure 2. Sketches of early concepts

Table 2. Concept evaluation

TCP Solution		Mill Solution	
• *Tool Center Point, with two rotational arms actuating simultaneously* • *A total of 5 motors for 5-axis actuation*		• *5-axis mill head* • *Two rotational joints acting simultaneously* • *A total of 5 motors for 5-axis actuation*	
Pros	**Cons**	**Pros**	**Cons**
Tool Center Point	Difficult to adjust once assembled	Stiff	Non tool center point
Light	Difficult for cabling, tubing and hosing	Used in other metal removal machines	Too heavy
Compact	Relatively weaker arms	commercially sold solution on the market	Difficult to add height sensor
Fewer Components	Large mass rotations when during cutting	Allows large range of cutting	
		Easy to adjust once assembled	
Robotic Arm		**Hexapod**	
• *Three rotational joints acting simultaneously* • *A total of 6 motors for actuation*		• *Three linear actuators acting simultaneously* • *A total of three ball screws, plus three motors(xyz)*	
Pros	**Cons**	**Pros**	**Cons**
Known solution in other industries	Non tool center point	Known solution in other industries	Non tool center point
commercially sold solution on the market	Too heavy	Easy for cabling, tubing and hosing	Structure would need to be significantly taller
Allows large range of cutting	Difficult to add height sensor	commercially sold solution on the market	Less range of cutting
Allows large range of	Structure would need to	Allows large range of	
Easy to adjust once assembled		Easy to adjust once assembled	

2.4 Concept selection

The evaluation of the concepts showed that the TCP-solution was superior and therefore the concept to go with. The company, Kimtech, also preferred this solution due to the advantages of minimizing the actuation needed when cutting and maximizing the available workspace on the cutting table as well as allowing for easy height measuring. The concept is shown in Figure 3.

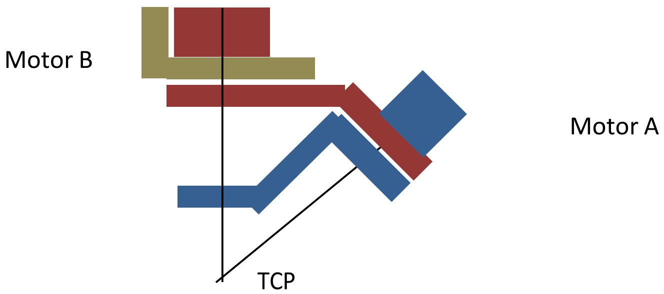

Figure 3. Principle layout of the selected concept

3. Concept analysis

Analysis work was based on the need to understand more about the deformations that occur during water jet cutting. The precision of the water jet cut proved to be a crucial point of discussion during the entire work process.

3.1 Mathematical description

The kinematic model can be described using a couple of angles and essentially two distances, *H* and *R*. *H* is the distance from the TCP to the mounting plane of motor B, while R is the perpendicular distance from motor A's axis of rotation to the mounting plane of motor B. The angles are the chamfer angle φ, motor A's angular displacement, α, motor B's displacement, β and the angle between the Z-axis and the axis of rotation of motor A, δ. These angles are illustrated in Figure 4.

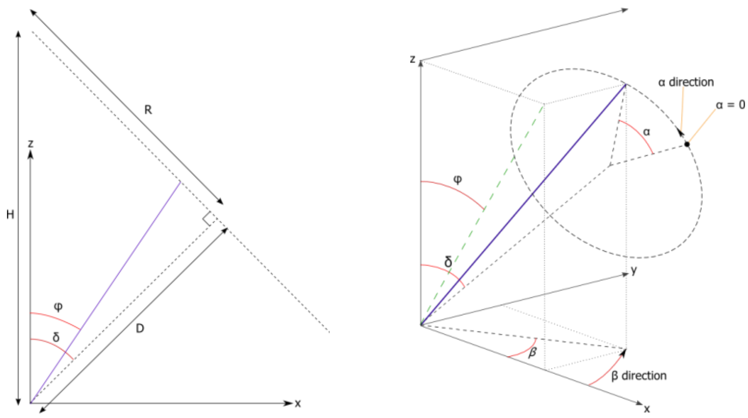

Figure 4. Angles and distances involved in kinematics illustrated.

The relationship converting the chamfer angle ϕ to the angular displacements, α and β, can be described using equation (1) and (2),

$$\alpha = \operatorname{asin}\left(\frac{D\tan(\delta-\varphi)}{R}\right) \tag{1}$$

$$\beta = \operatorname{atan}\left(\frac{R\cdot\cos(\alpha)}{D\sin(\delta) - R\sin(\alpha)\cos(\delta)}\right) \tag{2}$$

3.2 Multibody Simulations

Multibody simulations were performed in MSC Adams [9], and the main objective was the initial confirmation of motor capabilities, both in torque and angular velocity. The results were compared to the motor characteristics and proved to be satisfactory, see Figure 5.

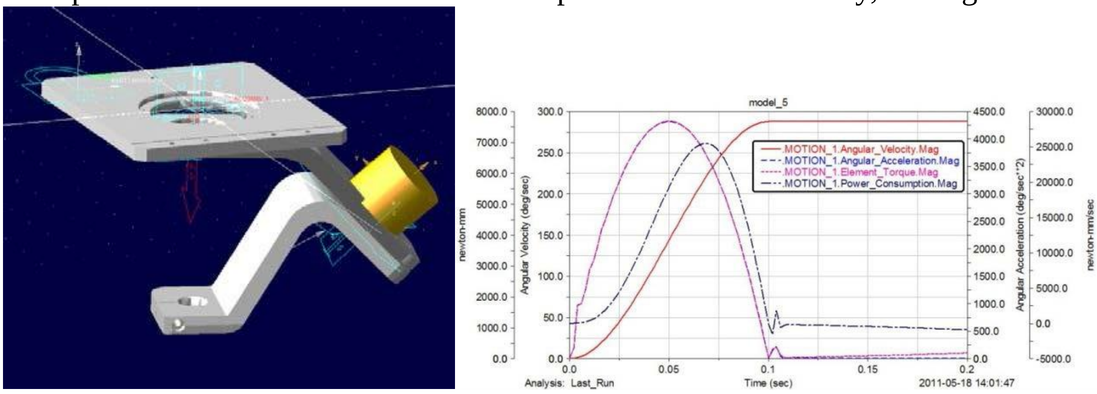

Figure 5. Multibody simulations done in MSC Adams

3.3 Finite Element Analysis

Finite element modeling was performed in ANSYS Workbench 13.0 [10] in which deformations were analyzed based on a force of 20 N from the water jet head. The geometry should allow a maximum deformation of 0.1 mm when the force is applied. The result from one of the analyses, showing the total deformation in Z-direction is shown in Figure 6.

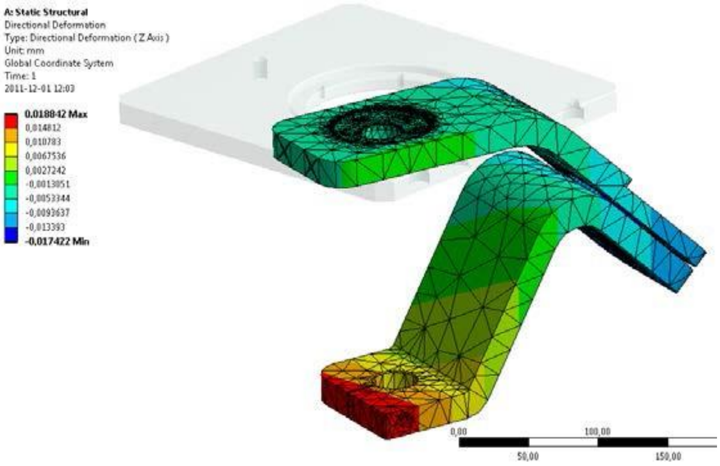

Figure 6. Resulting deformations in Z-direction

4. Detail Design

A top down approach was used throughout the design process. This approach starts with an overall sketch in the assembly file, and then links the sketch to component dimensions controlling the nominal dimensions from a top down approach. This method provides a good control over the parts and subassemblies due to the referenced master sketch.

The design of the head has been kept as small as possible due to the advantages it will bring in terms of weight, inertia and required motor. The dimensions of the auxiliary components set the limitations of the arm geometry. The motors, the mixing chamber assembly and the on/off valve gave the first rough dimensions for the head and the other parts. The angle of the upper arm was decided from the kinematic model. Figure 7 depicts an early rough sketch and dimensioning of the cutting head.

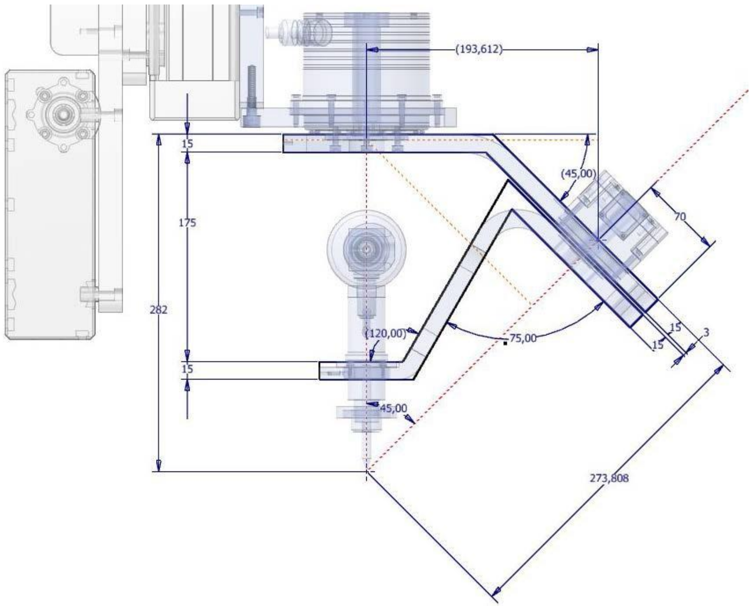

Figure 7. Measurements derived from the master sketch

4.1 Alpha prototype

Following the early sketches and drawings, the first prototype design, alpha prototype (see Figure 8 below), was built. The purpose was to test kinematic movements, view possible sources of error, check manufacturability and grant mechatronic students the ability to mount their components onto a structure. In this design no auxiliary components are attached. This design was performed during the summer (2011) to allow ample time for testing, and design for the beta prototype during the last part of the project.

However, given the complex geometry of the designed parts the supply of mechanical workshops being able to manufacture them within the tolerance limits proved to be a concern. The equipment needed is extensive, ranging from 5-axis CNC mills and expensive measuring equipment to verify that the parts were done correctly. Therefore, the alpha prototype could not acquire the accuracy level desired by the project group.

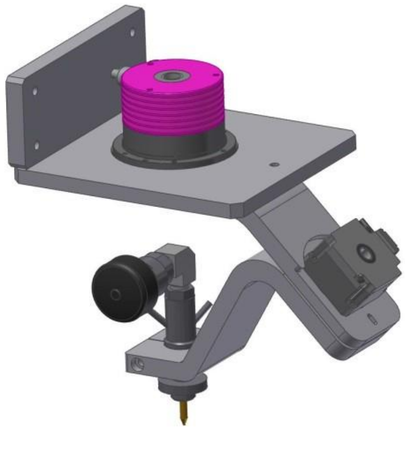

Figure 8. Alpha prototype

4.2 Beta prototype

The beta prototype, see Figure 9, was designed during September/October 2011. The focus of this prototype was to fix all errors found in the previous prototype and to adjust dimensions and features. For this prototype, FEM and MBS analysis were performed to optimize parameters such as weight and stiffness as shown before. Obtaining proper tolerances for the beta prototype proved an essential focus of the design, for this reason manufacturing procedures were developed for key components to ensure correct tolerances. Finally all auxiliary components, such as swivel mountings, routing, assembly fixtures, tubing, etc, were also designed.

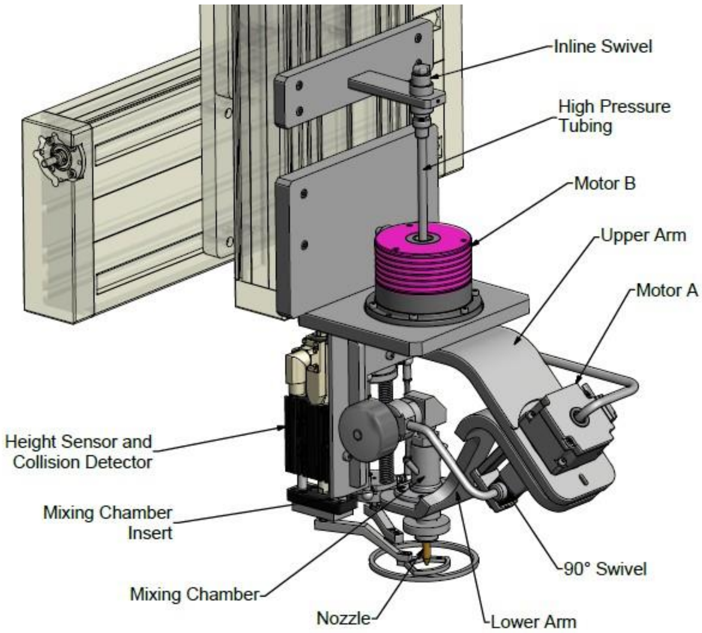

Figure 9. Beta prototype

4.3 Components

Actuators

As actuators it is preferred to use the Harmonic Drive motors [11] which the company already had and has been using in their existing 5-axis solution. First analyses made on the early design proved the motors to meet the requirements in terms of torque, power and speed. Harmonic drive actuators provide nearly backlash free motion, good resolution and repeatability. Additionally, these specific motors come with an open hollow shaft to route the cables and tubes through. This is an important feature due to the rotation in the arm caused by angled cutting, the hollow shaft makes it possible for the tubes and cables to follow the rotation. Thus, placing the tubing and the cabling through the axis of rotation will eliminate any twisting or redundant loads.

Mixing chamber

Mixing chamber is as the name states, the place where the sand and high-pressure water are mixed just before ejected through the nozzle. It needed to be relatively compact, high quality and has a cylindrical accurate surface that is very good for mounting on the lower arm. Additionally, its nozzle locking system is achieved by a tapered collet which ensures the nozzle is straight and rigid with respect to the mixing chamber

Swivels

Swivel basically refers to the connection between two tubes allowing rotation between them while at the same time enabling fluid to pass through. In the 5Ax head two different high pressure swivels which can work up to 400 MPa are used, one 90º and one straight in-line swivel, both with single axis rotation.

5. Conclusions and discussions

The biggest drawback of the old IHEAD design which is consisting of an abundance of moving parts is greatly eliminated with the new solution (5Ax). Actuating many linkages and parts to move the nozzle to the desired point leads to uncertainties and instability in the system which is not present in the new design. The close distance of the measurement equipment to the TCP also provides an advantage to 5Ax over the old design which caused various design, measuring and accuracy problems due to its elongated design. However, given the complex geometry of the designed parts the supply of mechanical workshops being able to manufacture them within the tolerance limits proved to be a concern. The equipment needed is extensive, ranging from 5-axis CNC mills and expensive measuring equipment to measure the parts to be done correctly. Therefore, the alpha prototype could not acquire the accuracy level desired by the project group. A beta prototype, was designed with the focus to fix all errors found in the previous prototype and to adjust dimensions and features. For this prototype, FEM and MBS analysis were performed to optimize parameters such as weight, and stiffness. Obtaining proper tolerances for the beta prototype proved to be essential for the design to work properly. For this reason, manufacturing procedures were developed for key components to ensure correct tolerances. The manufacturing of beta prototype is part of future work.

Most of the qualitative requirements set in the beginning are satisfied and the remaining points are either not testable with the current α prototype (“continuous cutting speed” and “make neat circles”) or not within the projects responsibility, such as the measuring. The 5Ax head fulfills the quantitative requirements but the opportunity to test the Z-axis accuracy has not yet been given since the α prototype wasn’t sufficient and the β prototype is not manufactured yet.

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